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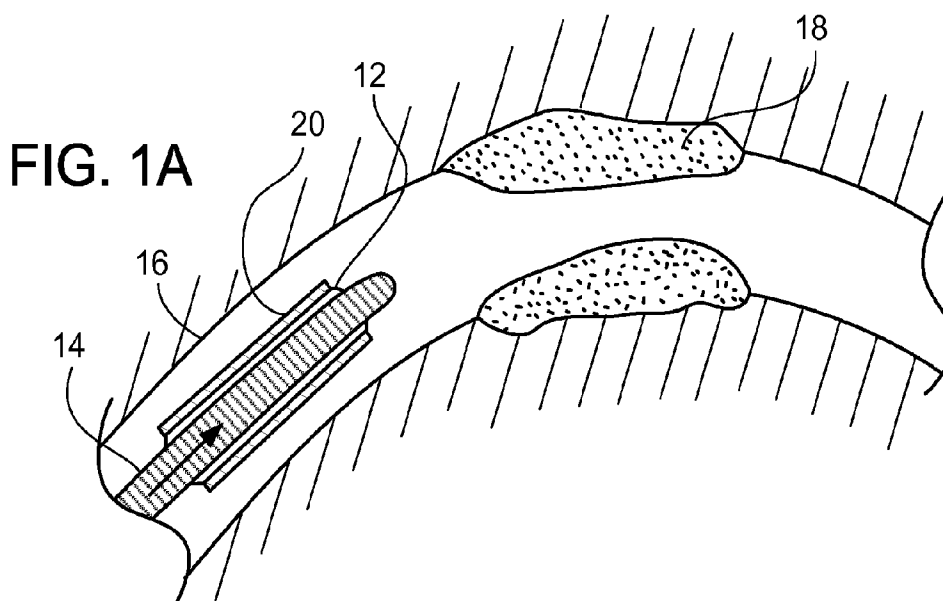
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(54) Title: STENT WITH EMBEDDED MATERIAL



(57) Abstract: An endoprosthesis such as a stent is composed of a metal or ceramic, such as Irox, embedded in the stent material.

Stent with Embedded Material

TECHNICAL FIELD

This disclosure relates to stents with embedded material.

BACKGROUND

5 The body includes various passageways such as arteries, other blood vessels, and other body lumens. These passageways sometimes become occluded or weakened. For example, the passageways can be occluded by a tumor, restricted by plaque, or weakened by an aneurysm. When this occurs, the passageway can be reopened or reinforced with a medical endoprosthesis. An endoprosthesis is typically a tubular member that is placed
10 in a lumen in the body. Examples of endoprostheses include stents, covered stents, and stent-grafts.

 Endoprostheses can be delivered inside the body by a catheter that supports the endoprosthesis in a compacted or reduced-size form as the endoprosthesis is transported to a desired site. Upon reaching the site, the endoprosthesis is expanded, e.g., so that it
15 can contact the walls of the lumen. Stent delivery is further discussed in Heath, U.S. Patent No. 6,290,721, the entire contents of which are incorporated by reference herein.

 The expansion mechanism may include forcing the endoprosthesis to expand radially. For example, the expansion mechanism can include the catheter carrying a balloon, which carries a balloon-expandable endoprosthesis. The balloon can be inflated
20 to deform and to fix the expanded endoprosthesis at a predetermined position in contact with the lumen wall. The balloon can then be deflated, and the catheter withdrawn from the lumen.

SUMMARY

25 In an aspect, the invention features an endoprosthesis including a metal having embedded therein a second metal or ceramic.

In another aspect, the invention features a method of adhering a ceramic to an endoprosthesis. The method includes embedding ceramic precursor particles into the endoprosthesis wall, and converting the precursor particles to ceramic.

Embodiments may also include one or more of the following features. The second metal or ceramic can be exposed at the surface of the endoprosthesis metal. The second metal or ceramic can be embedded to a depth of about one micron or less. The endoprosthesis can include a wall, and the second metal or ceramic can be embedded to a depth of about 1% or less of the thickness of the wall. The wall can be formed substantially of a single metal layer. The second metal or ceramic can be alloyed with the endoprosthesis metal. The second metal can be in the form of particles having a size of about one micron or less. The second metal or ceramic can be embedded in discontinuous regions of about one micron or less. The second metal can form a discontinuous coating on the surface of the endoprosthesis. The second metal can be selected from titanium, zirconium, hafnium, niobium, tantalum, ruthenium, iridium, and platinum. The ceramic can be an oxide. The ceramic can be Irox. The endoprosthesis metal can be stainless steel, chrome, nitinol, cobalt, chromium, nickel, titanium, tungsten, tantalum, rhenium, iridium, silver, gold, bismuth, platinum, superelastic alloys, or other alloys thereof.

Embodiments may also include one or more of the following features. The embedding can include melting the endoprosthesis wall to at least partially cover the precursor particles with the endoprosthesis wall material. The melting can include heating with a laser. The laser can be a pulsed laser, an excimer laser, a YAG laser, or a continuous wave laser. The embedding can include laser shock peening. The embedding can include embedding to a thickness of about 2 nm to 5 μm . The embedding can include alloying the precursor particles with the endoprosthesis wall. The converting can include oxidizing the precursor particles. The oxidizing can include electrochemical oxidation. The electrochemical oxidation can include cyclic voltammetry. The precursor particles can be deposited onto the surface of the endoprosthesis. The precursor particles can be deposited by sputtering, pulsed laser deposition, or chemical vapor deposition. The ceramic can be adhered on all exposed surfaces of the endoprosthesis. The ceramic can

be adhered only on the abluminal surfaces. The ceramic can be adhered only on the abluminal and surface surfaces.

Embodiments may include one or more of the following advantages. A stent, e.g. made of metal, can be provided with another material, such as a ceramic, e.g. iridium oxide (“Irox”), which can have beneficial therapeutic effects, such as reducing restenosis and encouraging endothelialization. The ceramic can be provided on the surface such that it is tightly adhered to the stent to reduce the likelihood that the material will be fractured, flake, or otherwise be dislodged from the stent. The coverage or concentration of the material on the surface can be controlled. The nature of the ceramic, such as the degree of oxidation can be carefully controlled, e.g. using electrochemical techniques. The material can be provided as small particles, and embedded in the outer surface of the stent so as to not excessively degrade the mechanical properties of the metal. Adhering the material to the stent and oxidizing the material can be performed in separate steps, which simplify processing and provide enhanced optimization. The oxide can be adhered directly to the surface of the stent metal, without using tie layers or abrasion unless desired.

Still further aspects, features, embodiments, and advantages follow.

DESCRIPTION OF DRAWINGS

FIGS. 1A-1C are longitudinal cross-sectional views illustrating delivery of a stent in a collapsed state, expansion of the stent, and deployment of the stent, respectively.

FIG. 2 is a perspective view of a stent.

FIG. 3 is a cross-sectional view of a stent wall showing metal particles embedded in the surface.

FIGS. 4A-4D are cross-sectional views of a stent wall illustrating schematically application of a ceramic. Fig. 4A illustrates deposition of particles onto the surface. Fig. 4B illustrates embedding the particles into the surface; Fig. 4C illustrates particles embedded in the surface; and Fig. 4D illustrates oxidation of the particles.

FIG. 5 is a schematic of a laser surface treatment system showing a laser system arranged to illuminate a stent in a chamber.

FIG. 6 is a schematic of an oxidation apparatus.

FIG. 7 is a cross-sectional view of a stent substrate showing particles embedded with alloying.

FIG. 8 is a cross-sectional view of a stent substrate showing particles embedded in a stent substrate that is highly irregular, with deep divots, etc., as would occur with a pulsed laser.

DETAILED DESCRIPTION

Referring to FIGS. 1A-1C, a stent 20 is placed over a balloon 12 carried near a distal end of a catheter 14, and is directed through the lumen 16 (FIG. 1A) until the portion carry the balloon and stent reaches the region of an occlusion 18. The stent 20 is then radially expanded by inflating the balloon 12 and compressed against the vessel wall with the result that occlusion 18 is compressed, and the vessel wall surrounding it undergoes a radial expansion (FIG. 1B). The pressure is then released from the balloon and the catheter is withdrawn from the vessel (FIG. 1C).

Referring to FIG. 2, the stent 20 includes a plurality of fenestrations 22 defined in a wall 23. Stent 22 includes several surface regions, including an outer, or abluminal, surface 24, an inner, or luminal, surface 26, and a plurality of cutface surfaces 28. The stent can be balloon expandable, as illustrated above, or self-expanding stent. Examples of stents are described in Heath '721, incorporated supra.

Referring to FIG. 3, stent wall 23, shown in cross-sectional view, includes a body 30, e.g. a metal such as stainless steel. The body includes stent surface 32, which may be any or all of the abluminal, luminal or cut surfaces, including a material, such as a ceramic, e.g. Irox, in the form of particles 50, 60. The material is embedded into the surface 32 and can include a plurality of exposed particles 50 and buried particles 60. The embedded material is tightly adhered to the stent material, which reduces the likelihood that the material will be dislodged while the stent is in use. The material is

embedded in the surface of the stent wall to a thickness of T_{90} , which is preferably a small percentage of the overall wall thickness, so that the presence of the material does not degrade the mechanical properties of the stent.

Referring to FIGS. 4A-4D, the material can be embedded by depositing a ceramic precursor metal onto the stent, melting a surface layer of the stent, cooling the stent, and then oxidizing the precursor metal to form the ceramic. Referring particularly to FIG. 4A, ceramic precursor particles 40 are deposited on stent surface 32 by e.g. physical vapor deposition. Referring particularly to FIG. 4B, the precursor is embedded by melting the surface of the stent metal, e.g. with a laser. Laser irradiation 36 causes localized melting to a thickness T_{92} (which substantially corresponds to thickness T_{90}). As the surface becomes soft or a liquid, particles are surrounded or partially surrounded by the stent metal. Referring to FIG. 4C, the surface is then allowed to cool, solidifying the stent metal about the precursor metal, and tightly adhering the precursor to the stent metal. Referring to FIG. 4D, the particles are then oxidized, e.g. in an electrochemical cell, to provide an embedded ceramic. Particles that are exposed 50 have been oxidized to produce regions of oxide 52.

Referring to FIG. 5, localized melting can be performed with a laser system 68, including an irradiation chamber 70 containing stent 20 held in place by a moveable clip 74 resting on a base 72, and a laser 76. The chamber 70 may be under vacuum, filled with an inert gas, or filled with a liquid. In one embodiment, chamber 70 may be under vacuum or filled with an inert gas so that irradiation of stent 20 by laser light causes local melting of stent wall, allowing particles to embed into the surface of stent wall. In another embodiment, chamber 70 may be filled with water so that irradiation of stent 20 by laser light effects laser shock peening at the stent surface, embedding particles into the stent wall. Chamber 70 may be made of any suitable material, optionally containing a window 78 allowing passage of laser light into the chamber. In an alternative embodiment, laser 76 may be located inside chamber 70.

In embodiments, sufficient laser energy is provided to melt the stent metal surface to a thickness T_{92} , which is about 5% or less, e.g., about 1% to 0.1% of the overall thickness of the stent metal. The thickness of the melted regions may be about 5% or

more of the particle diameter, e.g., about 25 to 200% of the particle diameter. In embodiments, the thickness of the melted region is about 5 nm to about 2 microns, e.g., 10 nm to 500 nm. In particular embodiments, the laser energy is sufficient to melt the stent metal but not to melt the ceramic precursor metal. Stainless steel, for example, has a lower melting temperature than iridium. In other embodiments, the laser energy is sufficient to cause melting or partial melting of both the precursor metal and stent metal, which can lead to alloying between the precursor and stent metal, which can enhance adherence. Laser alloying is further described in I. Manna et. al., *Micro-Structural Evaluation of Laser Surface Alloying of Ti with Ir*, Scripta Materialia 37(5) 561 (1997) and C. Tassin et. al., *Improvement of the Wear Resistance of 316 L Stainless Steel by Laser Surface Alloying*, Surface and Coating Technology 80(9), 207 (1996), the entire disclosure of each of which is hereby incorporated by reference herein. Alloying can reduce the sharpness of the discontinuity between the stent metal and the precursor alloy. The composition of the alloy can be graduated from pure stent metal to pure precursor metal, which enhances adhesion, and reduces the likelihood of dislodgement, e.g., as the stent is flexed in use. Suitable lasers include continuous wave or pulsed lasers. Suitable continuous wave lasers include CO₂ lasers. Suitable pulsed lasers include excimer lasers operating in the UV, or YAG lasers. A particular laser is a UV laser operating at a wavelength of 193 nm and a fluence of 300 mJ/cm² or greater. In other embodiments, the precursor metal can be embedded by techniques such as physical acceleration of the precursor particles into the surface of the stent metal, e.g. by kinetic spraying or laser shock peening. Spraying and laser shock peening methods are further discussed in U.S. Patent Application Publication No. 2005/0182478 and U.S. Patent Application No. 11/934,463, filed November 2, 2007, the entire disclosures of each of which is incorporated by reference herein.

Referring to FIG. 6, a system 78 for electrochemically oxidizing the precursor particles to ceramic includes a potentiostat 80, a reference electrode 82, a counter electrode 84, and stent 20 coated with precursor particles, each immersed in bath 86 filled with an electrolyte solution. In embodiments, the precursor metal is converted to oxide, i.e., ceramic, using cyclic voltammetry or other electrochemical techniques. In one

embodiment, cyclic voltammetry can be carried out utilizing an electrolyte solution such as a physiologic phosphate buffered saline solution. The degree of oxidation can be controlled by altering the electrochemical parameters, for example, the ranges of electrochemical potential and the number of cycles. In embodiments, the metal to oxygen ratio can range from about 1:1 to 1:2. Oxidation utilizing cyclic voltammetry and characterization of oxidized materials is further discussed in I.S. Lee et. al., *Biocompatibility and Charge Injection Property of Iridium Film Formed by Ion Beam Assisted Deposition*, Biomaterials 24, 2225 (2003); E.A. Irhayem et. al., *Glucose Detection Based on Electrochemically Formed Ir Oxide Films*, J. Electroanalytical Chem. 538, 153 (2002); and R.A. Silva et. al., *Electrochemical Characterization of Oxide Films Formed on Ti-6Al-4V Alloy Implanted with Ir for Bioengineering Applications*, Electrochimica Acta 43(102), 203 (1998), the entire disclosure of each of which is incorporated by reference herein. The surface of the medical device, e.g., of stainless steel, can be passivated during the electrolyte process. In embodiments, a drug is provided in the electrolyte such that it is incorporated into the particles during oxidation.

In embodiments, the ceramic precursor metal is a pure metal or an alloy such as titanium, zirconium, hafnium, niobium, tantalum, ruthenium, rhodium, iridium, platinum, and their alloys. Suitable ceramics include metal oxides and nitrides. Particular oxides provide therapeutic effects, such as enhancing endothelialization. A particular oxide is iridium oxide (Irox), which is further discussed in U.S. Patent No. 5,980,566 and U.S. Patent Application No. 10/651,562, filed August 29, 2003 (U.S. Patent Application Publication No. 2004-0039438), the entire disclosure of each of which is incorporated by reference herein. The precursor metal is preferably deposited in particulate form. For example, the particles can have a diameter that is small compared to the stent wall thickness, e.g., about 10% or less, e.g., 0.1% to 1% of the thickness or less. In embodiments, the particles have a diameter in the nanometer range to micron range, e.g., 1nm to about 1 micron, e.g., 200nm to 700nm. The particles are distributed such that they substantially cover a surface such as the abluminal surface, or partially cover the surface, e.g., 50% or less of the surface, leaving a desired pattern of the surface area exposed. In embodiments, the density of the particles on the surface is such that the entire

surface is covered. In other embodiments, the density of the particles is such that discrete regions are covered, with exposed stent metal between the regions. The distance between regions can be, e.g. about 1 μm or less. The particles can be deposited by sputtering techniques such as physical vapor deposition (PVD) and pulsed laser deposition (PLD), or by electrostatic or electrochemical deposition. Suitable PVD deposition techniques are described in X. Yan et. al., *New MOCVD Precursor for Iridium Thin Films Deposition*, Materials Letters 61, 216-218 (2007); U. Helmersson et. al., *Ionized Physical Vapor Deposition (IPVD): A Review of Technology and Applications*, Thin Solid Films 513, 1-24 (2006); and J. Singh and D.E. Wolfe, *Review: Nano and Macro-Structured Component Fabrication by Electron Beam-Physical Vapor Deposition (EB-PVD)*, Journal of Materials Science, 40, 1-26 (2005), U.S. Patent Application No. 11/752,736, filed May 23, 2007, and U.S. Patent Application No. 11/752,772, filed May 23, 2007, the entire disclosure of each of which is incorporated by reference herein.

In embodiments, the stent metal can be stainless steel, chrome, nickel, cobalt, tantalum, superelastic alloys such as nitinol, cobalt chromium, MP35N, and other metals. Suitable stent materials and stent designs are described in Heath '721, *supra*. In embodiments, the stent can include an outer layer of a different metal into which the precursor alloy is embedded, e.g., a titanium layer on a stent body formed of 316 stainless steel. A particular advantage of other embodiments is that the precursor particles can be embedded directly into a superficial region of the stent metal without treatment of the stent, such as the deposition of a separate metal layer or roughening the surface

In one embodiment, ceramic is adhered only on the abluminal surface of the stent. This construction may be accomplished by, e.g., coating precursor particles on a stent material before forming the fenestrations. In another embodiment, ceramic is adhered only on abluminal and cutface surfaces of the stent. This construction may be accomplished by, e.g., coating precursor particles on a stent containing a mandrel, which shields the luminal surfaces from deposition by precursor particles. In each of these embodiments, the stent may then be treated with a laser to embed the precursor particles, and the precursor particles may then be oxidized to form regions of embedded ceramic only on the abluminal and/or cutface surfaces.

Referring to FIG. 7, in embodiments, precursor particles 50 (and 60) are embedded into the surface, such that regions 54 (and 64) of the interface of the particles and the stent metal are composed of a matrix of the precursor and stent metal, such as an alloy. An alloy is formed by heating to a temperature sufficient to melt both the stent metal and the particles. The alloying can be performed simultaneously with embedding the particles by heating the particles above their melting point. Alternatively, embedding and alloying can be performed sequentially. For example, in a first step, particles can be embedded, e.g., by heating to a temperature above the stent metal melting point but below the particle metal melting point. In a subsequent step, the embedded assembly is heated above the melting point of the particles and stent metal to cause co-melting and mixing. In embodiments, only a portion of the particles are alloyed with adjacent stent metal. In other embodiments, substantially the entire particle is alloyed with the stent metal, providing a domain of alloyed metal. In embodiments, the particles can be coated or partially coated with a second metal. The second metal can facilitate alloying. For example, the second metal can be selected to have a melting temperature that is below the melting temperature of the primary metal of the particle to facilitate co-melting with the stent metal without melting the primary metal of the particle. The second metal can be selected for its capacity to form a desired alloy with the stent metal or the primary particle metal to provide desirable mechanical properties.

Referring to FIG. 8, in embodiments, the morphology, roughness, or porosity of the stent surface is controlled. A stent surface 36 is roughened to contain pits, grooves, and other surface irregularities 90. Such surface may contain exposed embedded precursor particles 50 and/or buried embedded precursor particles 60. The stent may also contain void spaces 92 which may be produced by regions of stent wall 30, by regions of precursor particles, or by some combination thereof. A functional molecule, e.g. an organic, drug, polymer, protein, DNA, and similar materials can be incorporated into grooves, pits, void spaces, and other features of the roughened stent surface. Suitable functional molecules include D-Phe-Pro-Arg chloromethyl ketone, an RGD peptide-containing compound, heparin, hirudin, antithrombin compounds, platelet receptor antagonists, anti-thrombin antibodies, anti-platelet receptor antibodies, aspirin, paclitaxel,

prostaglandin inhibitors, platelet inhibitors and tick antiplatelet peptides. Such molecules are further described in U.S. Patent Application No. 11/111,509, filed April 21, 2005 (U.S. Patent Application Publication. No. 2005/0251249), the contents of which are incorporated by reference herein. In other embodiments, a drug containing polymer layer
5 can be applied to the surface containing embedded particles. The adhesion of the polymer can be enhanced by the roughened surface. In other embodiments, embedding the particles as described above provides sufficient roughness without the formation of pits and grooves. Suitable polymers and drugs are described in U.S. Patent Application Nos. 11/752,736 and 11/752,772, both filed May 23, 2007, the entire disclosure of each
10 of which is incorporated by reference herein.

The roughened surface can be formed during or after the particles are embedded or formed in the ceramic. In embodiments, the roughened surface is formed using a pulsed laser, e.g., an excimer laser. The shots from the laser can form divots in the surface. The size, depth and number of divots can be controlled by controlling the
15 wavelength, fluence, pulse width, number of pulses, and location of pulses. The divots can be formed simultaneously while embedding the particles. Alternatively, the divots can be formed before or subsequently to embedding the particles. In other embodiments, the surface is roughened by other techniques, e.g., by etching, mechanical bombardment or laser shock peening technique. In embodiments, the porosity formed by laser
20 techniques can be controlled, e.g., decreased, by subsequent short peen treatment of the surface to close divots. The divots can be formed on part or all of the stent surfaces. The divots can be formed in a pattern, e.g., lines running along the stent axis. In embodiments, the depth of the divots is e.g. five times or less than the particle size, e.g. about 0.5 to twice the particle size. In embodiments, the depth of the divots is about 5 μ
25 or less, e.g., 0.5 micron to 2 microns.

As discussed above, particles can be deposited as a precursor metal which is subsequently oxidized. An advantage of this technique is that exposure of the oxide to high temperature such as melting temperatures at which the oxide can degrade can be minimized. In other embodiments, oxide particles can be deposited directly, e.g. by
30 oxidizing metal during PVD. An advantage of this technique is that an oxidation step

after embedding may not be performed. In embodiments, embedding can be performed during particle deposition, e.g. by focusing laser energy on the deposited surface during PVD. The laser illumination can be varied to embed particles at desired locations.

Nonembedded particles can be removed by washing.

5 The process can be performed on a stent precursor, e.g., a base metal tube or the stent. In other embodiments, particles are embedded by depositing the particles as to a metal precursor tube, and then drawing the tube to smaller diameters to forge the particles into the stent metal. A mask can be used to prevent depositing at undesired locations. For example, a mandrel can be used to shield the interior of the stent. The process can be
10 used with other endoprostheses or medical devices, such as catheters, guide wires, and filters.

 All publications, patent applications, and patents cited above are incorporated by reference herein in their entirety.

 Still other embodiments are in the following claims.

WHAT IS CLAIMED IS:

1. An endoprosthesis comprising a metal having embedded therein a second metal or ceramic.

5

2. The endoprosthesis of claim 1 wherein the second metal or ceramic is exposed at the surface of the endoprosthesis metal.

10

3. The endoprosthesis of claim 1 wherein the second metal or ceramic is embedded to a depth of about one micron or less.

15

4. The endoprosthesis of claim 1 wherein the endoprosthesis includes a wall, and the second metal or ceramic is embedded to a depth of about 1% or less of the thickness of the wall.

5. The endoprosthesis of claim 4 wherein the wall is formed substantially of a single metal layer.

20

6. The endoprosthesis of claim 1 wherein the second metal or ceramic is alloyed with the endoprosthesis metal.

7. The endoprosthesis of claim 1 wherein the second metal is in the form of particles having a size of about one micron or less.

25

8. The endoprosthesis of claim 1 wherein the second metal or ceramic is embedded in discontinuous regions of about one micron or less.

9. The endoprosthesis of claim 1 wherein the second metal forms a discontinuous coating on the surface of the endoprosthesis.

30

10. The endoprosthesis of claim 1 wherein the second metal is selected from among titanium, zirconium, hafnium, niobium, tantalum, ruthenium, iridium, and platinum.

5 11. The endoprosthesis of claim 1 wherein the ceramic is an oxide.

12. The endoprosthesis of claim 1 wherein the ceramic is Irox.

10 13. The endoprosthesis of claim 1 wherein the endoprosthesis metal is selected from among stainless steel, chrome, nitinol, cobalt chromium, nickel, titanium, tungsten, tantalum, rhenium, iridium, silver, gold, bismuth, platinum, superelastic alloys, and other alloys thereof.

15 14. A method of adhering a ceramic to an endoprosthesis, comprising embedding ceramic precursor particles into an endoprosthesis wall; and converting the precursor particles to ceramic.

20 15. The method of claim 14 wherein embedding includes melting the endoprosthesis wall to at least partially cover the precursor particles with endoprosthesis wall material.

16. The method of claim 15 wherein the melting includes heating with a laser.

25 17. The method of claim 16 wherein the laser is selected from among a pulsed laser, an excimer laser, a YAG laser, and a continuous wave laser.

18. The method of claim 14 wherein embedding includes laser shock peening.

30 19. The method of claim 14 wherein embedding includes embedding to a thickness of about 2 nm to 0.5 μm .

20. The method of claim 14 wherein embedding includes alloying the precursor particles with the endoprosthesis wall.

5 21. The method of claim 14 wherein converting includes oxidizing the precursor particles.

22. The method of claim 21 wherein oxidizing includes electrochemical oxidation.

10 23. The method of claim 22 wherein electrochemical oxidation includes cyclic voltammetry.

15 24. The method of claim 14 further comprising depositing the precursor particles onto the surface of the endoprosthesis.

25. The method of claim 24 wherein the precursor particles are deposited by sputtering, pulsed laser deposition, or chemical vapor deposition.

20 26. The method of claim 14 wherein ceramic is adhered on all exposed surfaces of the endoprosthesis.

27. The method of claim 16 wherein ceramic is adhered only on the abluminal surfaces.

25 28. The method of claim 16 wherein ceramic is adhered only on the abluminal and cutface surfaces.

FIG. 1A

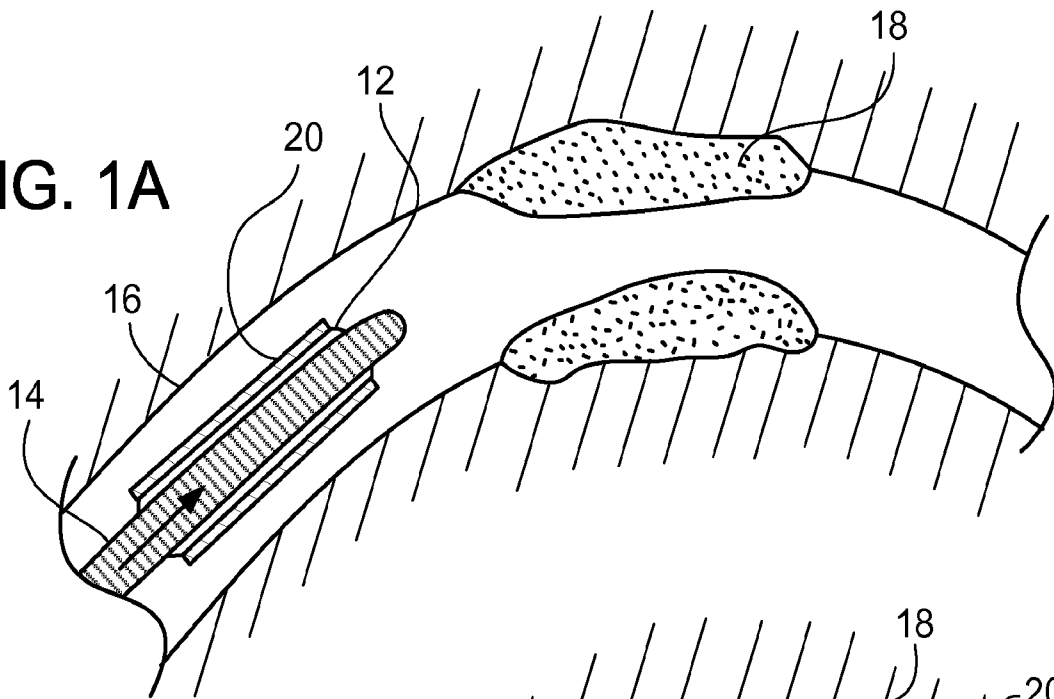


FIG. 1B

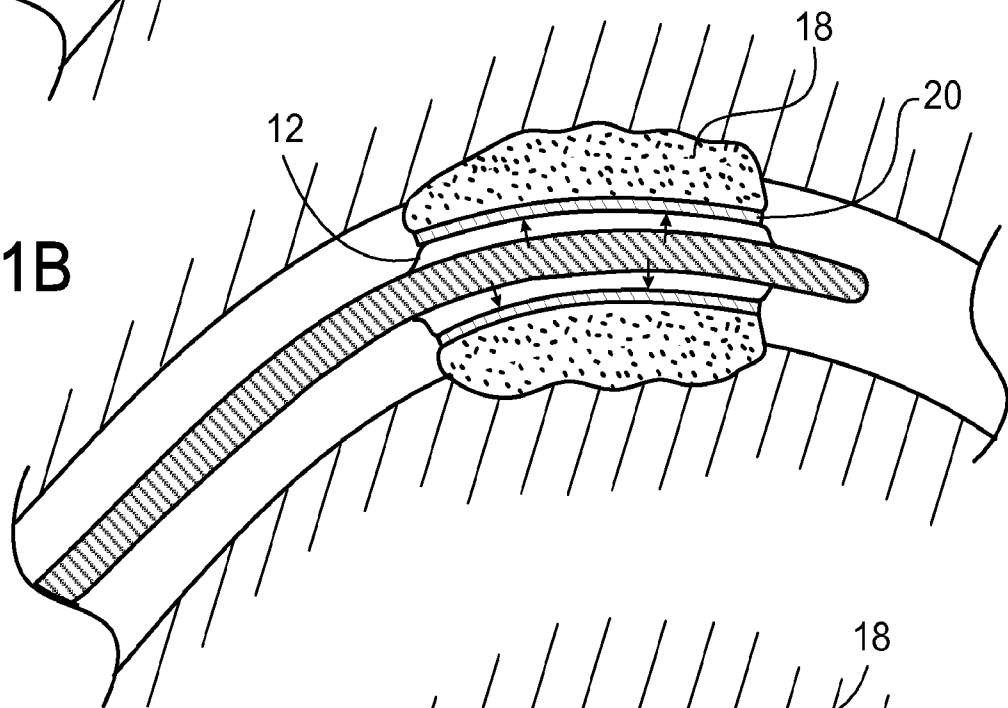
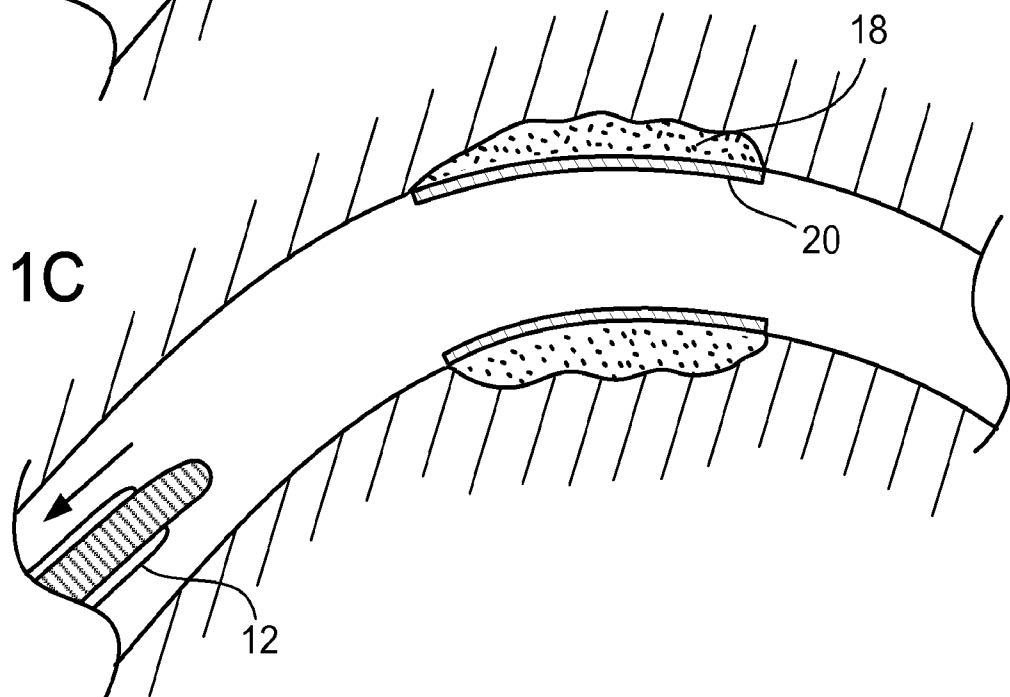
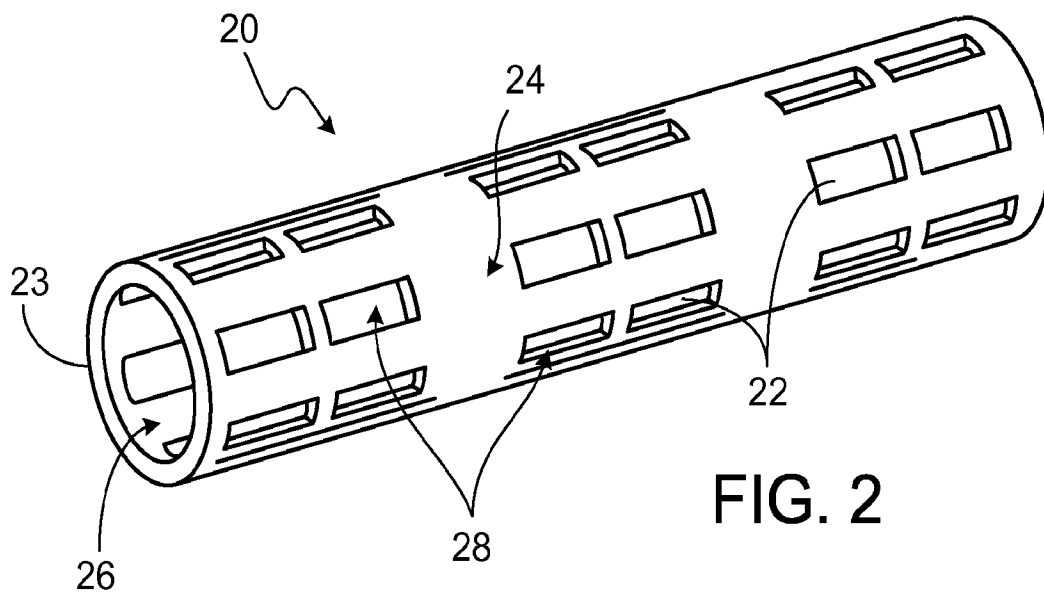


FIG. 1C





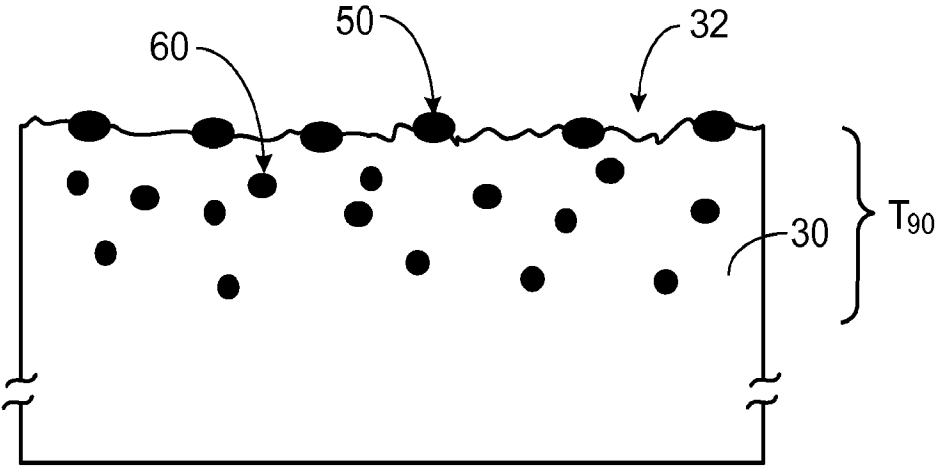


FIG. 3

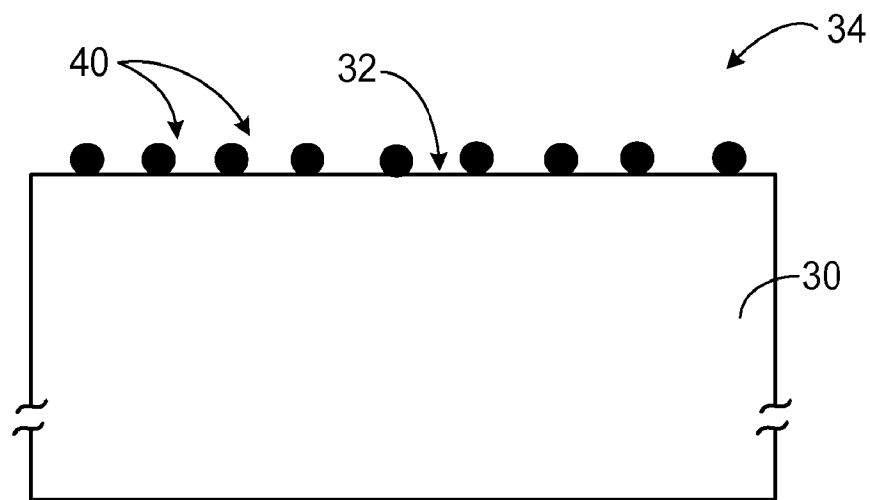


FIG. 4A

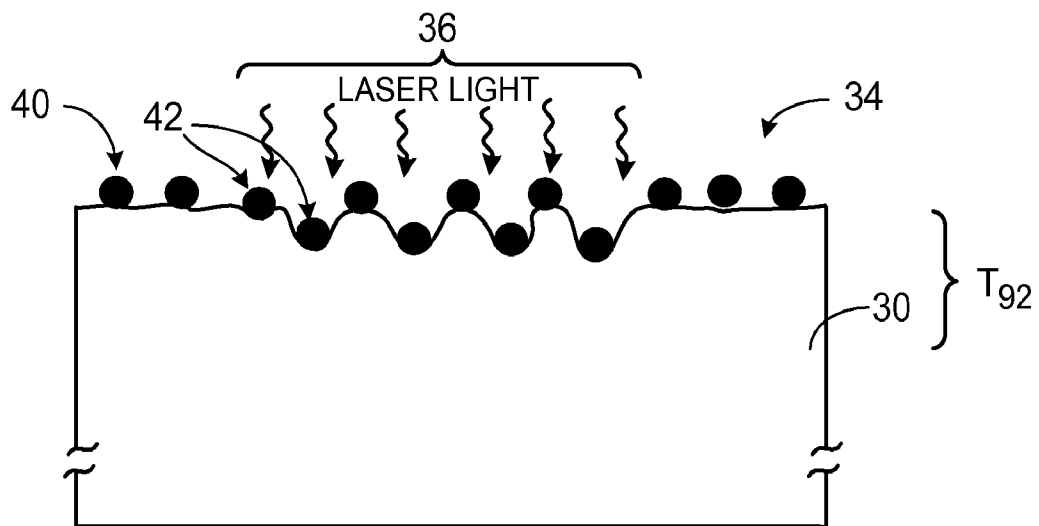


FIG. 4B

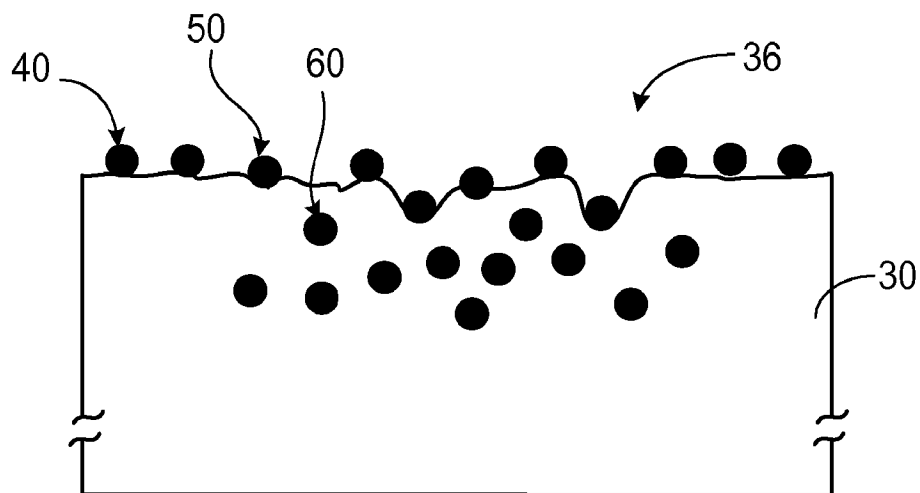


FIG. 4C

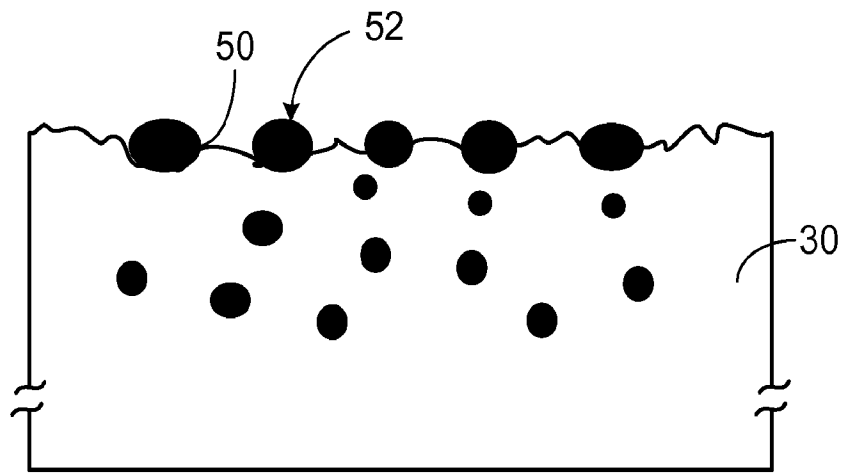


FIG. 4D

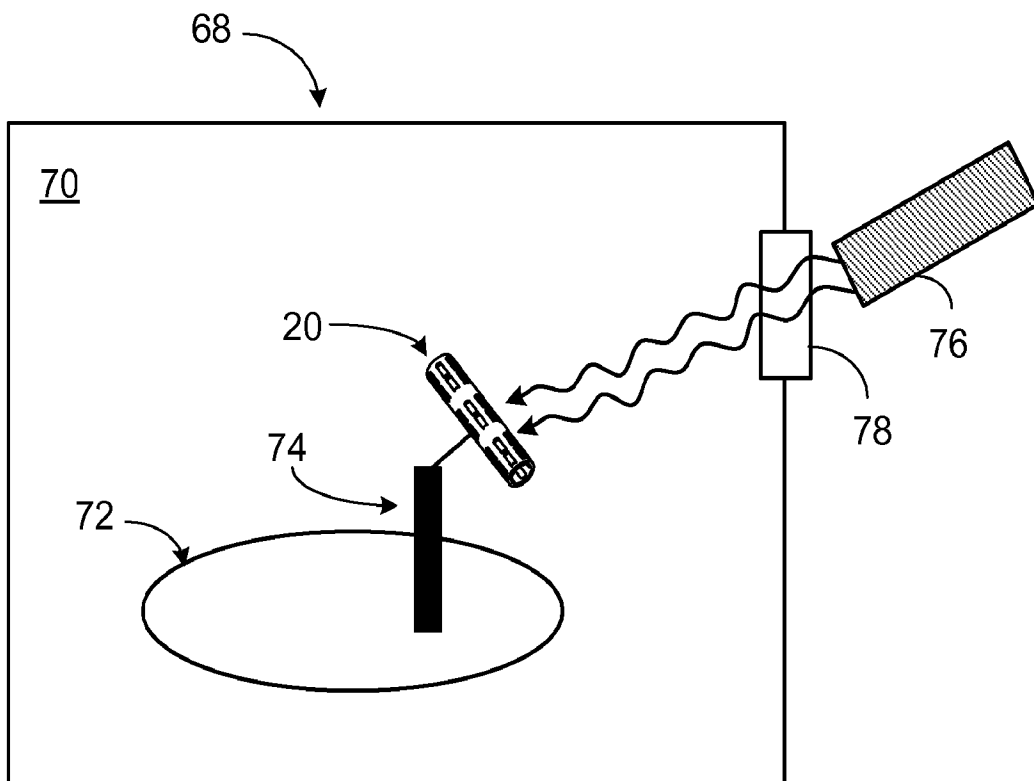


FIG. 5

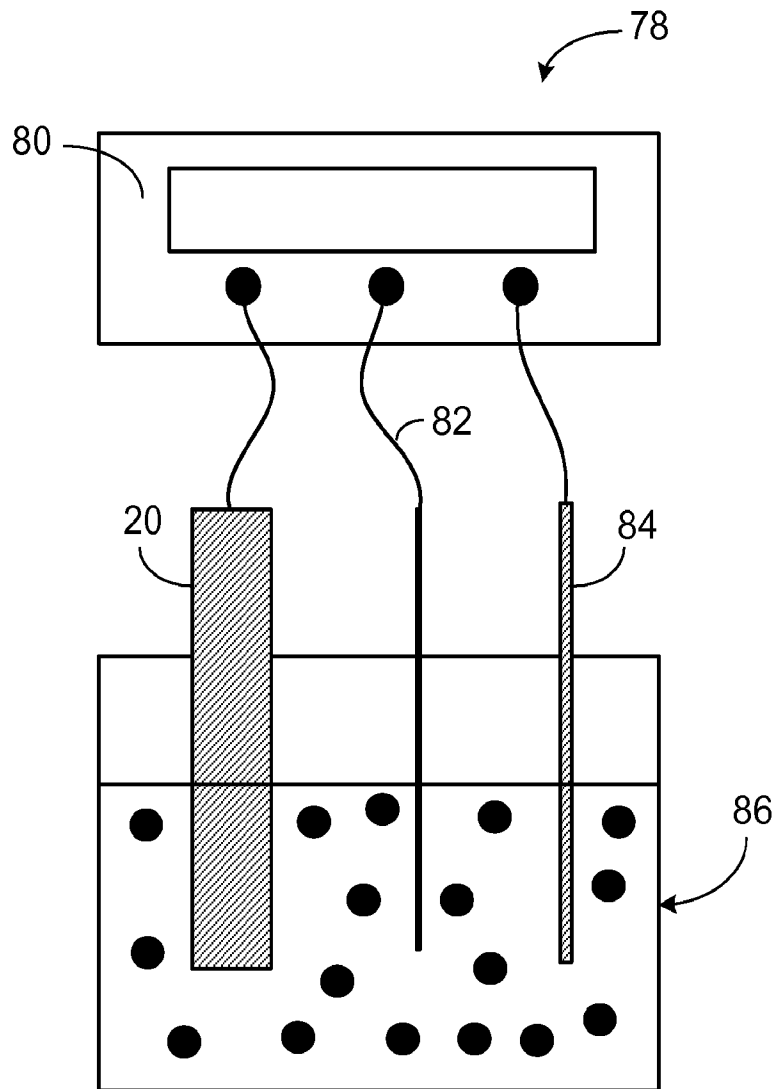


FIG. 6

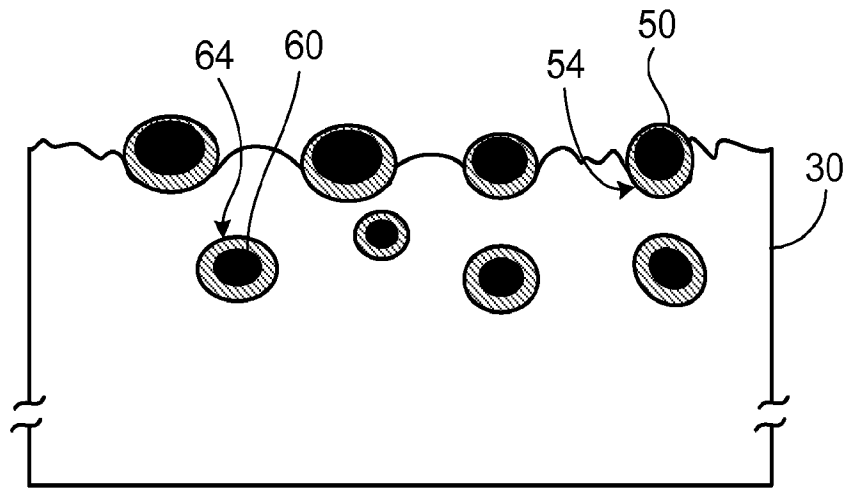


FIG. 7

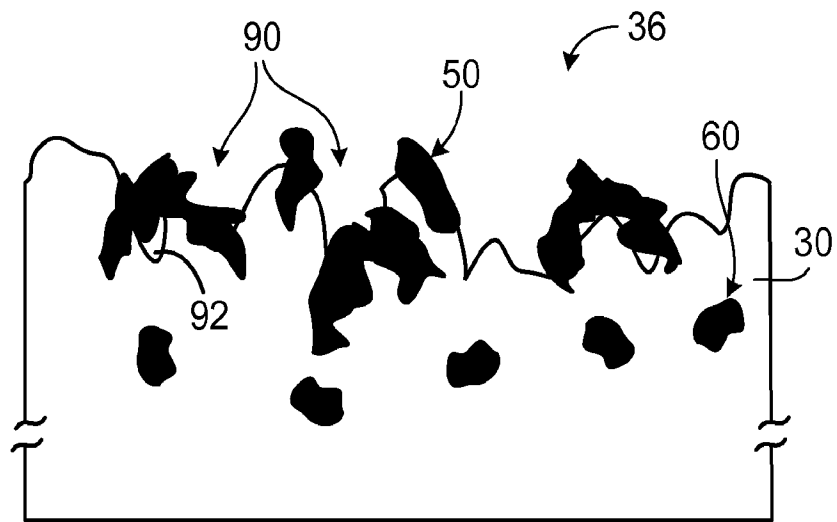


FIG. 8