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[Continued on next page]

(54) Title: MEDICAL IMPLANT

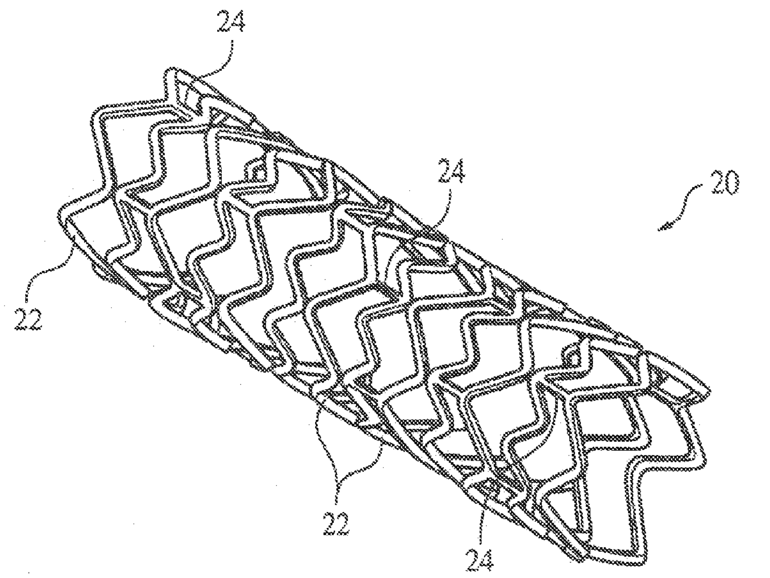

FIG. 1

(57) Abstract: A endoprosthesis includes a body comprising a plurality of interconnected struts. The body includes a bioerodible metal. At least a first strut of the plurality of interconnected struts includes a stripe on the surface of the first strut. The stripe including a nitride of the bioerodible metal, a fluoride of the bioerodible metal, or a combination thereof. The stripe runs along the length of the first strut. The stripe is part of a continuous network of stripes on struts adjacent to the first strut.

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— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

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Medical Implant

TECHNICAL FIELD

This invention relates to medical implants, and more particularly to endoprostheses.

BACKGROUND

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, or even replaced, with an endoprosthesis. An endoprosthesis is typically a tubular member that is placed in a lumen in the body. Examples of endoprostheses include stents, covered stents, stent-grafts, and vascular closure pins.

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, for example, so that it can contact the walls of the lumen.

The expansion mechanism can 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 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 The balloon can then be deflated, and the catheter withdrawn.

In another delivery technique, the endoprosthesis is formed of an elastic material that can be reversibly compacted and expanded, e.g., elastically or through a material phase transition. During introduction into the body, the endoprosthesis is restrained in a compacted condition. Upon reaching the desired implantation site, the restraint is removed, for example, by retracting a restraining device such as an outer sheath, enabling the endoprosthesis to self-expand by its own internal elastic restoring force.

Some endoprostheses are designed to erode under physiological conditions so that most of the material of the endoprosthesis is naturally removed from the implantation site after a specific period of time.

SUMMARY

An endoprosthesis is described that includes a body including a plurality of interconnected struts and a stripe on the surface of a first strut of the plurality of interconnected struts. The body including a bioerodible metal and the stripe including a nitride of the bioerodible metal, a fluoride of the bioerodible metal, or a combination thereof. The stripe running along the length of the first strut. The stripe being part of a continuous network of stripes on struts adjacent to the first strut.

The bioerodible metal can include iron or an alloy thereof and/or magnesium or an alloy thereof. In some embodiments, the bioerodible metal of the body can have nano-crystal grains and a plurality of corrosion barrier layers in or between the nano-crystal grains. The corrosion barrier layers can include a metal nitride, a metal fluoride, or a combination thereof.

The stripe can have a maximum width of 250 micrometers and a minimum thickness of 100 nanometers. In some embodiments, the first strut includes no more than one stripe. In some embodiments, the body is adapted for expansion from an initial diameter to an expanded diameter and includes a plurality of deformation points due to the expansion and at least one deformation point includes a plurality of stripes. The plurality of stripes can be a part of the continuous network. In some embodiments, the stripe can includes a gradient from a surface adjacent to the bioerodible metal of the first strut having first percentage of nitride, fluoride, or combination thereof to an outer surface having a second percentage of nitride, fluoride, or combination thereof greater than the first percentage.

The first strut can also include a corrosion delaying layer surrounding the first strut. The corrosion delaying layer can have a smaller thickness than a thickness of the stripe. The corrosion delaying layer can include a metal nitride, a metal fluoride, or a combination thereof.

The endoprosthesis, in some embodiments, can be a stent.

In another aspect, a medical implant is described that includes a body that includes a metal having nano-crystal grains and a plurality of corrosion barrier layers in or between the nano-crystal grains. The corrosion barrier layers can include a metal nitride, a metal fluoride, or a combination thereof. In some embodiments, the metal can be bioerodible. In some embodiments, the medical implant can include a

metal nitride of the metal. In some embodiments, the medical implant can be an endoprosthesis (e.g., a stent).

In another aspect, a method of forming an endoprosthesis is described that includes using a pulsed laser to transform a surface portion of a body comprising a bioerodible metal into a nitride of the bioerodible metal, a fluoride of the bioerodible metal, or a combination thereof. The body includes a plurality of interconnected struts. The body is positioned within a nitrogen and/or fluorine environment during the application of the pulsed laser. In some embodiments, the surface portion of the body transformed into a nitride of the bioerodible metal, a fluoride of the bioerodible metal, or a combination thereof forms a continuous network extending along a plurality of the interconnected struts. In some embodiments, the continuous network includes at least one stripe has a maximum width of 250 micrometers and a minimum thickness of 100 nanometers. In some embodiments, the pulsed-laser is a nanosecond pulsed laser. In some embodiments, the method further includes forming the body by sintering a plurality of nanocrystaline bioerodible metal particles to produce the body including a metal body having nano-crystal grains and a plurality of corrosion barrier layers in or between the nano-crystal grains. The plurality of metal particles including metal particles comprising a metal nitride, a metal fluoride, or a combination thereof, which form the corrosion barrier layers. In some embodiments, endoprosthesis is a stent.

The details of one or more embodiments are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. 1 is a perspective view of an embodiment of an expanded stent.

FIG. 2A is a perspective view of an embodiment of a stent strut.

FIG. 2B is a cross-sectional view of the stent strut of FIG. 2A.

FIG. 2C is a perspective view of the stent strut of FIG. 2A after the partial erosion of the stent strut.

FIG. 2D is a perspective view of an embodiment of a stent strut.

FIG. 3A and 3B depict a process of producing a nitrided stripe.

FIG. 4A is a perspective view of an embodiment of a stent strut.

FIG. 4B is a cross-sectional view of the stent strut of FIG. 4A.

FIGS. 5A-5C depict different stages of a method for producing a stent having corrosion barrier layers.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Referring to Fig. 1, a stent 20 can have the form of a tubular member defined by a plurality of struts. The struts can include a plurality of bands 22 and a plurality of connectors 24 that extend between and connect adjacent bands. During use, bands 22 can be expanded from an initial, small diameter to a larger diameter to contact stent 20 against a wall of a vessel, thereby maintaining the patency of the vessel. Connectors 24 can provide stent 20 with flexibility and conformability that allow the stent to adapt to the contours of the vessel.

The stent includes a bioerodible metal. Examples of bioerodible metals include iron, magnesium, tungsten, zinc, and alloys thereof. For example, the bioerodible metal can be a bioerodible iron alloy that includes up to twenty percent by weight manganese, up to 10 percent by weight silver, and up to five percent by weight carbon. The bioerodible metal can also be a bioerodible magnesium alloy that includes up to nine percent aluminum, up to five percent rare earth metals, up to five percent zirconium, up to five percent lithium, up to five percent manganese, up to ten percent silver, up to five percent chromium, up to five percent silicon, , up to six percent yttrium, up to ten percent zinc. Suitable magnesium bioerodible alloys include ZK31, which includes three percent zinc and one percent zirconium, ZK61, which includes six percent zinc and one percent zirconium, AZ31, which includes three percent aluminum and one percent zinc, AZ91, which includes nine percent aluminum and one percent zinc, WE43, which includes four percent yttrium and three percent rare earth metals, and WE54, which includes five percent yttrium and four percent rare earth metals. A stent including a bioerodible metal can reinforce a reopened body passageway, yet breakdown over time so that the stent is no longer present in the body passageway after a healing process is complete and the passageway no longer needs reinforcement. Different bioerodible metals and stent strut structures can have different erosion rates when exposed to a physiological environment. Accordingly, the stent can be designed based on the erosion characteristics of the stent struts to maintain the desired structural properties for a desired period of time.

The stent also includes a nitride of the bioerodible metal, a fluoride of the bioerodible metal, or a combination thereof. Nitrides of bioerodible metal include iron nitride, Fe_2N; magnesium nitride, Mg_3N_2; zinc nitride, Zn_3N_2; and tungsten nitride, WN_2. A nitride of a bioerodible metal can have a higher erosion resistance than the bioerodible metal when the stent is implanted within a physiological environment. The inclusion of nitrides can also alter the hardness, wear resistance, corrosion resistance, and/or yield strength of the bioerodible metal.

As shown in Figs. 2A-2D, a stent strut (e.g., a band 22 and/or a connector 24) includes a body 26 including a bioerodible metal and a stripe 28 including a nitride of the bioerodible metal, a fluoride of the bioerodible metal, or a combination thereof. For example, the body 26 can include iron or an alloy thereof and the stripe 28 can include iron nitride, Fe_2N. The body 26 forms the plurality of interconnected struts of the tubular member. The stripe 28 runs along the length of the strut 22 or 24. The stripe 28 is part of a continuous network of stripes of the nitride of the bioerodible metal on adjacent struts.

The continuous network of stripes of nitride and/or fluoride of the bioerodible metal allows for areas surrounding the stripe 28 to erode when implanted within a physiological environment at a faster rate than the stripe 28. The presence of the continuous network of stripes can allow for a connection between different portions of the stent as the body 26 erodes within a physiological environment, for example as shown in FIG. 2C. This connection reduces the instance and size of portions of the bioerodible body separating from the remainder of the stent and migrating downstream of the implantation site.

The stripe can have a width of between 5 micrometers and the entire width of the strut , whereby the width of the stripe can be altered along the stripe by adjusting the optical system. Although Figure 2A shows the stripe to be in the middle of the strut, it will be clear that the stripe can be positioned along the entire circumference of the strut. In some embodiments, the stripe can have a width of between 10 micrometers and 30 micrometers (e.g., about 20 micrometers). An Excimer laser, as discussed below, can be focused down to a 5 micrometer spot size, which can allow for nitrided and/or fluorided stripes as thin as five to ten micrometers. A stent strut can have a width of between 250 and 50 micrometers. The size of the stripe 28 to the diameter of the stent strut 22 or 24 can result in a minimal reduction in the erosion rate of the bioerodible metal body 26, yet can provide a network connecting different portions of different struts even as the body erodes within a physiological environment. As shown in FIGS. 2A-2C, some embodiments includes stent struts 22 or 24 having a single nitrided stripe 28.

Areas of the stent having higher stress levels can have additional metal nitrides and/or metal fluorides than the surrounding areas of the stent in some embodiments. For example, the bends in the bands 22 can experience additional stress due the expansion of the stent. These deformation points can therefore experience a faster rate of erosion. The additional metal nitrides and/or metal fluorides can reduce the initial mass needed in high stress areas and can maintain the desired mechanical performance after an initial amount of erosion. As shown in FIG. 2D, a bend in a band 22 can include multiple stripes 29 of a nitrides and/or a fluorides of the bioerodible metal encasing the bend. The multiple stripes 29 can remain connected to the continuous network of the nitrides and/or fluorides of the bioerodible metal.

The stripe 28 can include a gradient of nitride and/or fluoride from a surface adjacent to the bioerodible metal body 26 to an outer surface, with the outer surface having a higher percentage of nitrides and/or fluorides.

The stripe 28 can be formed on the surface of the body by transforming the bioerodible metal of a precursor of the body into a nitride and/or floride of the continuous network. For example, pulsed-laser nitriding is one method of forming a nitrided stripe 28 on the surface of body 26. FIGS. 3A and 3B depict an example of a pulsed-laser nitriding process. For example, a stent 20 can be placed within a nitriding chamber 32 containing nitrogen. In some embodiments, the nitriding chamber 32 can be substantially free of oxygen and/or carbon dioxide. Portions of the stent body 26 are then subject to pulses of a laser at varying wavelengths and pulse times. For example, body 26 can be subject to nanosecond Excimer laser pulses (55 ns), Nd-doped yttrium aluminum garnet (Nd:YAG) laser pulses (8 ns), and/or ultra short Ti-sapphire laser pulses (150 fs). As shown in FIG. 3A, an XeCl Excimer laser 34 can be directed to and focused on a portion of a stent body 26 to produce a nitrided stripe 28. A Fly Eye Homogenizer 36 and/or other optical element can be used to direct and focus the laser pulses onto a particular location of the stent body 26. Additionally, a movable table 38 can be used to move the stent body 26 during the nitriding process. As shown in FIG. 3B, the laser can create a plasma at the focus point and can create a molten metal 27 along the surface of the stent body 26. The process can result in a gradient of nitride within the stripe having a higher concentration of nitride along the outer surface of the resulting stent. The pulse time and power of the laser can impact the thickness of the nitrided stripe 28. The advantage of a pulsed laser such as an excimer laser is that the surface can repeatedly be molten during a very short timeframe in the order of the pulse time of the laser, whereby the excited nitrogen gas can diffuse and react with the molten layer. The diffusion distance is a function of the pulse during which the surface material is molten. The concentration of the nitrided layer is determined as such by the number of pulses and the nitrogen concentration in the surrounding atmosphere, whereas the depth of the nitrided layer is depending on the energy density in the pulse and the number of pulses. A nitrided surface of 1 micrometer can be achieved using for example a 700 mJ pulse energy / square mm irradiation. Besides using a nitrogen atmosphere to achieve a nitriding effect, the use of fluorine gas can within a chamber can achieve a fluoridizing effect. As shown in FIG. 3B, the stripe can have a thickness of about 1 micrometer.

Stent 20 can also include a corrosion delaying layer 42 of a nitride and/or floride of the bioerodible metal surrounding the exposed surfaces of the stent body 26. The corrosion delaying layer 42 can have an approximately constant thickness. The thickness of the corrosion delaying layer 42 is between 0.1 and 5 nanometers. For example, as shown in FIGS. 4A and 4B, the stent strut body 26 can include corrosion delaying layer 42 around the circumference of the stent strut. The stent also includes a nitrided and/or fluorided stripe 28, which remains after the corrosion delaying layer 42 erodes away and the stent body 26 erodes to help keep the plurality of stent struts connected. The corrosion delaying layer 42 has a smaller thickness than stripe 28. For example, the corrosion delaying layer 42 can be produced by nitriding the entire surface of a stent strut with a pulsed femtosecond laser, which can create a nitrided layer having a thickness of about 1 nanometer in thickness, while the continuous network of a nitrided stripe can be produced with pulsed nanosecond laser, such as the Excimer laser discussed above, to produce a stripe having a thickness of about 1 micrometer. For example, a description of a laser nitriding process is described in Laser Nitriding of Metals, Influences of the Ambient Pressure and the Pulse Duration, Meng Han, Gottingen 2001, which is hereby incorporated by reference.

The stent can have a body including a metal having nano-crystal grains and a plurality of corrosion barrier layers in or between the nano-crystal grains. The corrosion barrier layers can include a metal nitride, a metal fluoride, or a combination thereof.

A stent body having metal nitride and/or metal fluoride corrosion barrier layers in or between the nano-crystal grains can be produced by a powder sintering and nitriding/fluoridizing process. For example, a powder of a metal can be produced by mechanical milling (MM). For example, a ball mill can be used at room temperature in an argon gas or other atmosphere to produce a metal powder. The mechanically milled or mechanically alloyed powders are easily reduced down to a crystal grain diameter of about 10 to 20 nm by mechanical energy applied by ball milling. Examples of mechanical milling processes are described in U.S. Patent Application No. 2006/0127266, which is hereby incorporated by reference.

The metal powder can be a bioerodible metal, such as those described above. In some embodiments, the metal powder includes only a single metal, such as iron, without the presence of alloying elements. In other embodiments, the metal powder can be an alloy.

The metal powder can be partially nitrided and/or fluorided before a sintering process. The partial nitriding and/or fluoridizing of the metal powder prior to the sintering process can result in a stent body having increased mechanical strength and internal corrosion barriers. For example, FIG. 5A depicts a nanocrystaline iron powder put into a layer in a flat pan. The flat pan can then be placed within a nitriding chamber and portions of powder can be nitrided. FIG. 5B depicts a nanocrystaline iron powder in the flat pan partially treated with laser nitriding. Additionally, metal powder could be separated into two groups, with only one group being nitrided. The groups could then be mixed and/or layered prior to sintering. Additionally, the ratios of the nitrided to non-nitrided metal powders can be varied for different portions of a resulting stent.

The partially nitrided metal powder can then be sintered to create metal having metal nitride and/or fluoride corrosion barrier layers in or between the nano-crystal grains. For example, the metal powder can be vacuum charged into a stainless steel tube (sheath) for forming-by-sintering by means of sheath rolling using a rolling machine at a temperature that is about 10% lower than the melting temperature of the metal powder. Examples of sintering processes are described in U.S. Patent Application No. 2006/0127266, which is hereby incorporated by reference.

The sintered metal can then be shaped into a medical device, such as stent 20. FIG. 5C depicts a stent strut 22 or 24 including the sintered metal structure that includes a bulk structure that resembles a marble cake. For example, the sintered metal can then be shaped into a stent by forming a tube out of the sintered metal and cutting the tube to form bands 22 and connectors 24 to produce an unfinished stent. Areas of the unfinished stent affected by the cutting can be subsequently removed. The unfinished stent can be finished to form stent 20. Finishing can include, for example, polishing or other surface treatments and/or application of drug-eluting coatings. In some embodiments, finishing the stent can further include producing a network of nitrided and/or fluorided stripes and/or to producing a corrosion delaying layer 42, as discussed above. In other embodiments, the sintered metal can be shaped into other medical devices such as orthopedic implants; bioscaffolding; bone screws; aneurism coils, and other endoprostheses such as covered stents and stent-grafts.

Stent 20 can be of any desired shape and size (e.g., superficial femoral artery stents, coronary stents, aortic stents, peripheral vascular stents, gastrointestinal stents, urology stents, and neurology stents). Depending on the application, the stent can have a diameter of between, for example, 1 mm to 46 mm. In certain embodiments, a coronary stent can have an expanded diameter of from 2 mm to 6 mm. In some embodiments, a peripheral stent can have an expanded diameter of from 5 mm to 24 mm. In certain embodiments, a gastrointestinal and/or urology stent can have an expanded diameter of from 6 mm to about 30 mm. In some embodiments, a neurology stent can have an expanded diameter of from about 1 mm to about 12 mm. An Abdominal Aortic Aneurysm (AAA) stent and a Thoracic Aortic Aneurysm (TAA) stent can have a diameter from about 20 mm to about 46 mm.

The stent 20 can, in some embodiments, be adapted to release one or more therapeutic agents. The term “therapeutic agent” includes one or more “therapeutic agents” or “drugs.” The terms “therapeutic agents” and “drugs” are used interchangeably and include pharmaceutically active compounds, nucleic acids with and without carrier vectors such as lipids, compacting agents (such as histones), viruses (such as adenovirus, adeno-associated virus, retrovirus, lentivirus and a-virus), polymers, antibiotics, hyaluronic acid, gene therapies, proteins, cells, stem cells and the like, or combinations thereof, with or without targeting sequences. The delivery mediated is formulated as needed to maintain cell function and viability. A common example of a therapeutic agent includes Paclitaxel.

The stent 20 can, in some embodiments, also include one or more coatings overlying the surface portion 32. In some embodiments, a surface coating can further delay the erosion of the surface portion 32. In some embodiments, a coating can be a drug-eluting coating that includes a therapeutic agent.

Stent 20 can be used, e.g., delivered and expanded, using a catheter delivery system. Catheter systems are described in, for example, Wang U.S. 5,195,969, Hamlin U.S. 5,270,086, and Raeder-Devens, U.S. 6,726,712. Stents and stent delivery are also exemplified by the Sentinol® system, available from Boston Scientific Scimed, Maple Grove, MN.

In some embodiments, stents can also be a part of a covered stent or a stent-graft. In other embodiments, a stent can include and/or be attached to a biocompatible, non-porous or semi-porous polymer matrix made of polytetrafluoroethylene (PTFE), expanded PTFE, polyethylene, urethane, or polypropylene.

In some embodiments, stents can be formed by fabricating a wire having a nitrided stripe 28, nitride corrosion barrier layers, and/or a corrosion delaying layer 42 and knitting and/or weaving the wire into a tubular member.

All publications, references, applications, and patents referred to herein are incorporated by reference in their entirety.

Other embodiments are within the claims.

WHAT IS CLAIMED IS:

1. A endoprosthesis comprising:

a body comprising a plurality of interconnected struts, the body comprising a bioerodible metal, and

at least a first strut of the plurality of interconnected struts including a stripe on the surface of the first strut, the stripe comprising a nitride of the bioerodible metal, a fluoride of the bioerodible metal, or a combination thereof, the stripe running along the length of the first strut, the stripe being part of a continuous network of stripes on struts adjacent to the first strut.

2. The endoprosthesis of claim 1, wherein the bioerodible metal comprises iron or an alloy thereof.

3. The endoprosthesis of claim 1, wherein the bioerodible metal comprises magnesium or an alloy thereof.

4. The endoprosthesis of claim 1, wherein the stripe has a maximum width of 250 micrometers and a minimum thickness of 100 nanometers.

5. The endoprosthesis of claim 1, wherein the first strut comprises no more than one stripe.

6. The endoprosthesis of claim 1, wherein the body is adapted for expansion from an initial diameter to an expanded diameter and comprises a plurality of deformation points due to the expansion, wherein at least one deformation point includes a plurality of stripes, the plurality of stripes being part of the continuous network.

7. The endoprosthesis of claim 1, wherein the stripe includes a gradient from a surface adjacent to the bioerodible metal of the first strut having first percentage of nitride, fluoride, or combination thereof to an outer surface having a second percentage of nitride, fluoride, or combination thereof greater than the first percentage.

8. The endoprosthesis of claim 1, wherein the first strut further comprises a corrosion delaying layer surrounding the first strut, the corrosion delaying layer having a smaller thickness than a thickness of the stripe, the corrosion delaying layer comprising a metal nitride, a metal fluoride, or a combination thereof.

9. The endoprosthesis of claim 1, wherein the bioerodible metal of the body has nano-crystal grains and a plurality of corrosion barrier layers in or between the nano-crystal grains, the corrosion barrier layers comprising a metal nitride, a metal fluoride, or a combination thereof.

10. A medical implant comprising a body that includes a metal comprising nano-crystal grains and a plurality of corrosion barrier layers in or between the nano-crystal grains, the corrosion barrier layers comprising a metal nitride, a metal fluoride, or a combination thereof.

11. The medical implant of claim 10, wherein the metal is bioerodible.

12. The medical implant of claim 10, wherein the medical implant comprises a metal nitride of the metal.

13. The medical implant of claim 10, wherein the medical implant is an endoprosthesis.

14. The medical implant of claim 10, wherein the medical implant is stent.

15. A method of forming an endoprosthesis comprising:

using a pulsed laser to transform a surface portion of a body comprising a bioerodible metal into a nitride of the bioerodible metal, a fluoride of the bioerodible metal, or a combination thereof, the body including a plurality of interconnected struts, the body being positioned within a nitrogen and/or fluorine environment during the application of the pulsed laser.

16. The method of claim 15, wherein the surface portion of the body transformed into a nitride of the bioerodible metal, a fluoride of the bioerodible metal, or a combination thereof forms a continuous network extending along a plurality of the interconnected struts.

17. The method of claim 16, wherein the continuous network includes at least one stripe has a maximum width of 250 micrometers and a minimum thickness of 100 nanometers.

18. The method of claim 15, wherein the pulsed-laser is a nanosecond pulsed laser.

19. The method of claim 15, further comprising forming the body by sintering a plurality of nanocrystaline bioerodible metal particles to produce the body including a metal body having nano-crystal grains and a plurality of corrosion barrier layers in or between the nano-crystal grains, the plurality of metal particles comprising metal particles comprising a metal nitride, a metal fluoride, or a combination thereof, which form the corrosion barrier layers.

20. The method of claim 15, wherein the endoprosthesis is a stent.

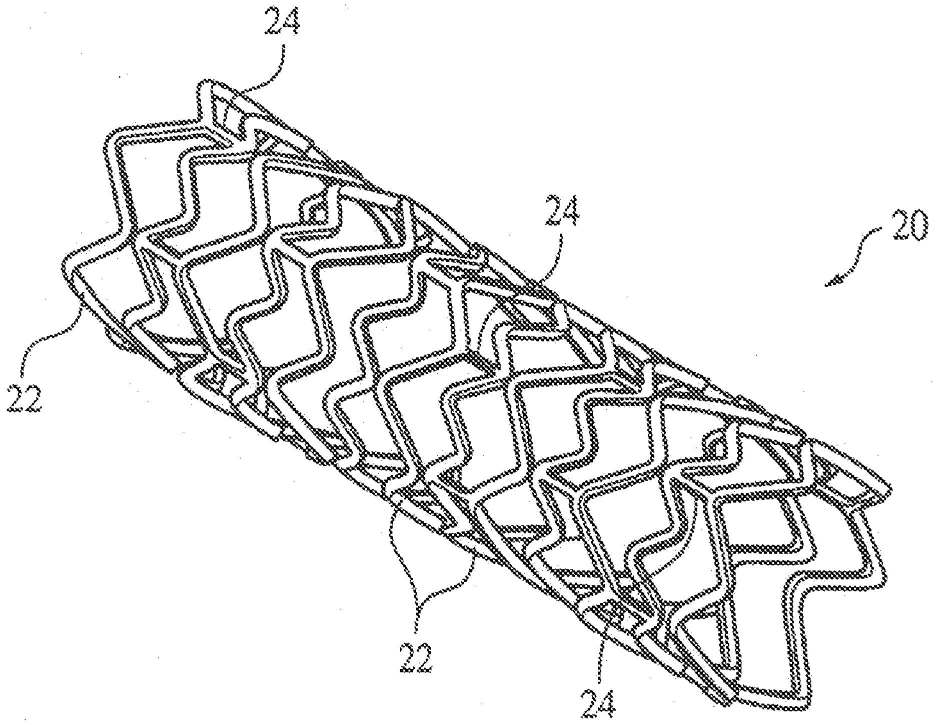


FIG. 1

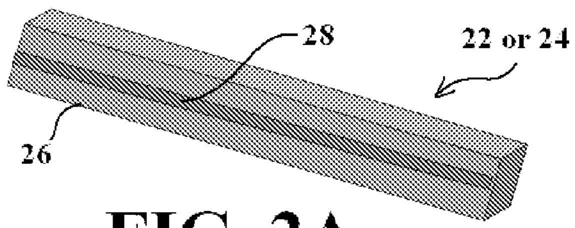


FIG. 2A

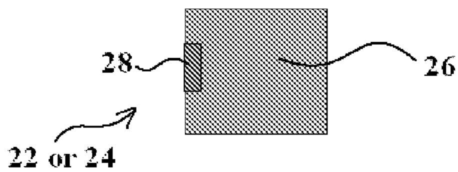


FIG. 2B

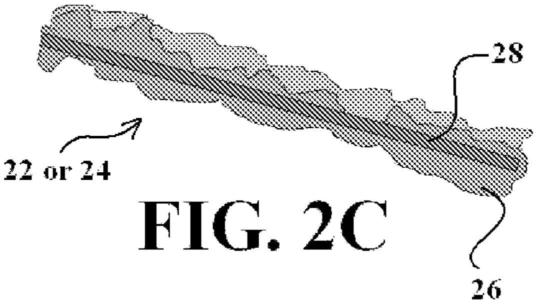


FIG. 2C

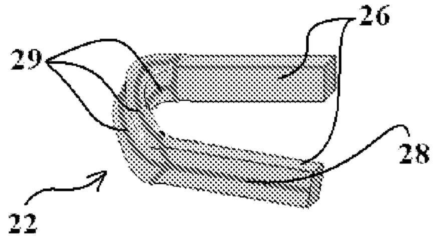


FIG. 2D

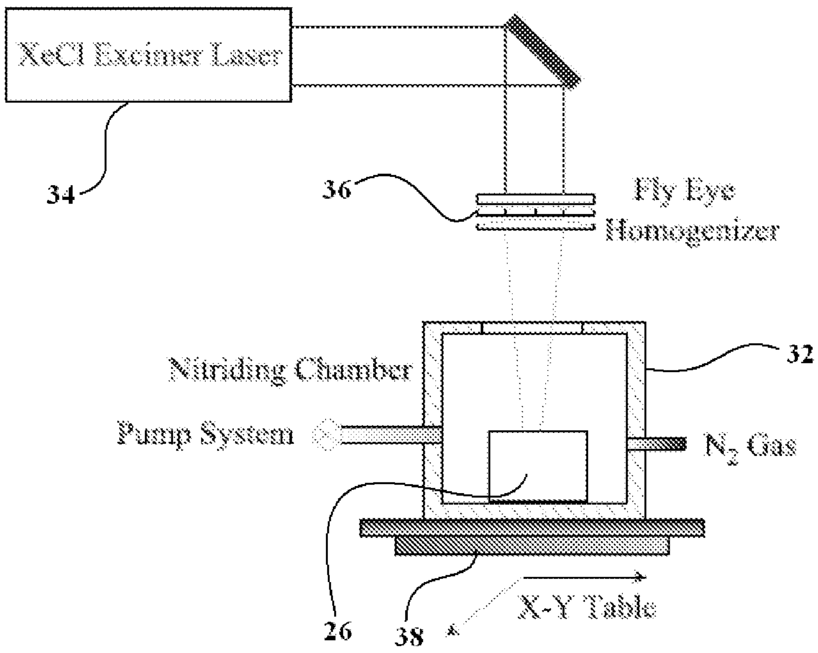

XeCl Excimer Laser
34
36
Fly Eye Homogenizer
Nitriding Chamber
32
Pump System
N_2 Gas
26
38
X-Y Table

FIG. 3A

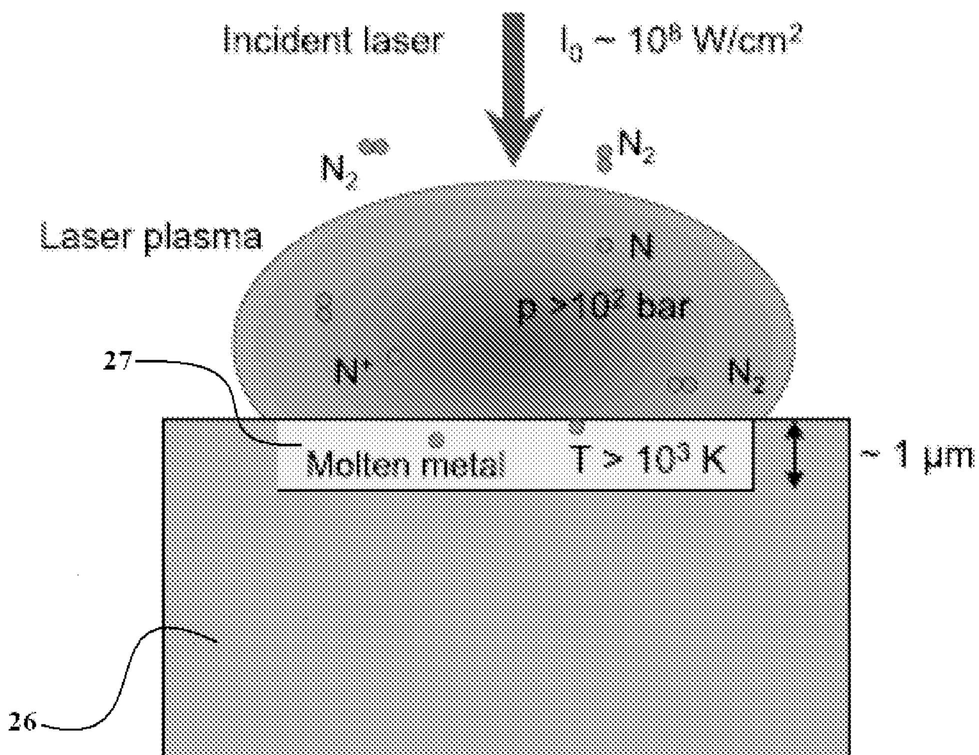

Incident laser
I_0 ~ 10^8 W/cm^2
N_2
N_2
Laser plasma
N
p >10^2 bar
27
N^+
N_2
Molten metal
T > 10^3 K
~ 1 µm
26

FIG. 3B

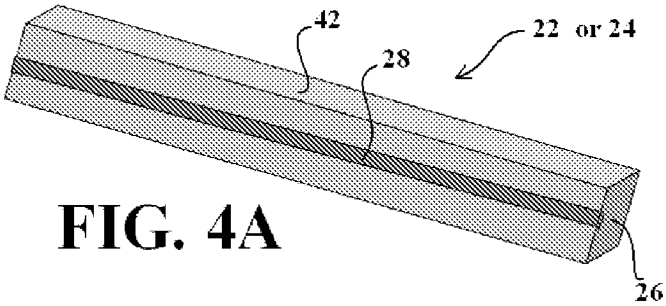
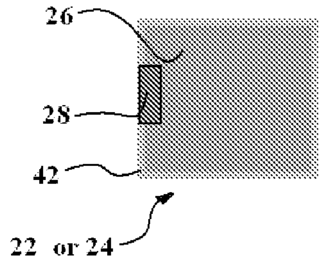


FIG. 4A

FIG. 4B



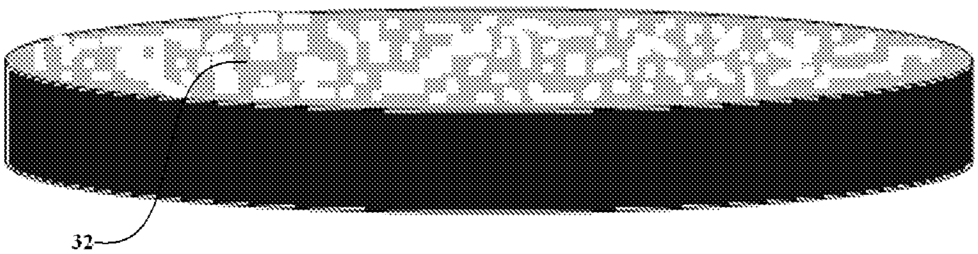


FIG. 5A

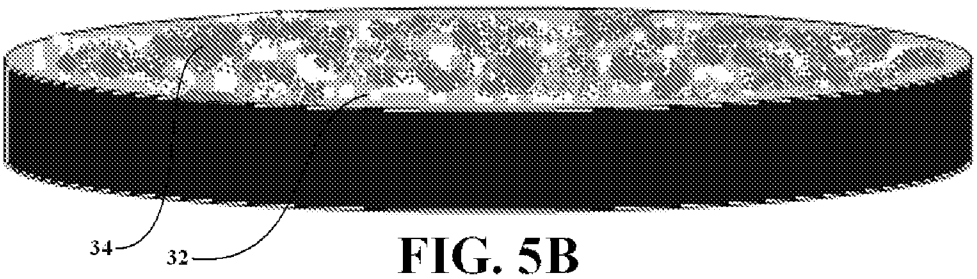


FIG. 5B

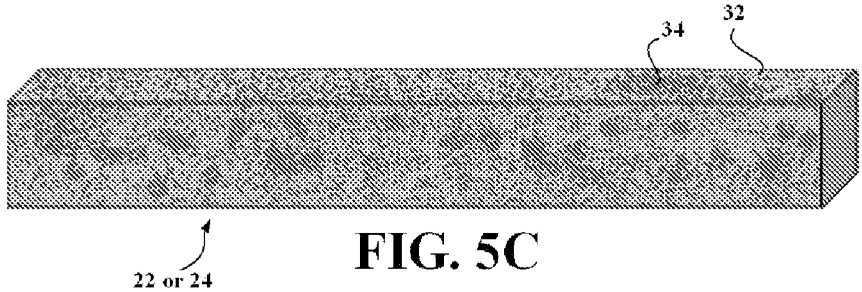


FIG. 5C