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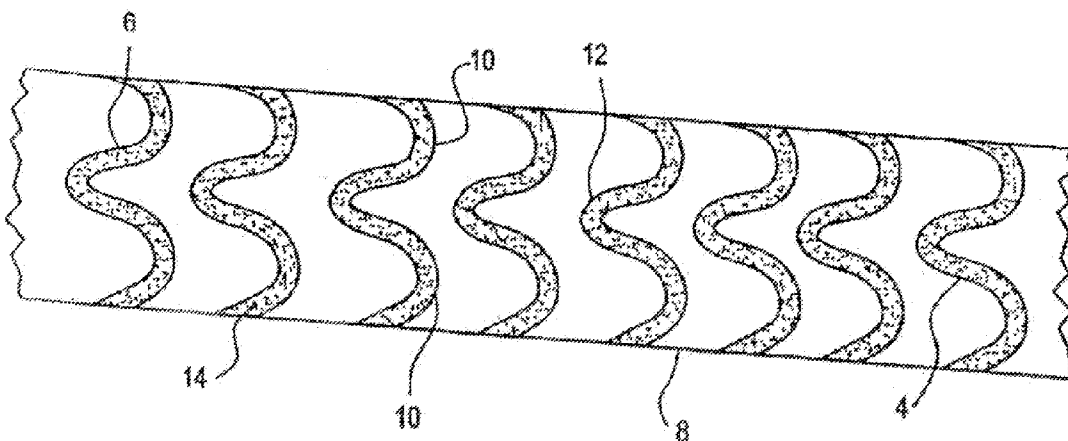
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(54) Title: **ENDOPROSTHESIS WITH THREE-DIMENSIONAL DISINTEGRATION CONTROL**



(57) Abstract: The present invention comprises a medical device having a support structure made from alternating layers.

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ENDOPROSTHESIS WITH THREE-DIMENSIONAL DISINTEGRATION CONTROL

FIELD OF THE INVENTION

[0001] This invention relates to medical devices, such as endoprostheses, and methods of
5 making such devices.

BACKGROUND

[0002] The body includes various passageways including blood vessels such as arteries, and other body lumens. These passageways sometimes become occluded or weakened. For example, they can be occluded by a tumor, restricted by plaque, or weakened by an
10 aneurysm. When this occurs, the passageway can be reopened or reinforced, or even replaced, with a medical endoprosthesis. An endoprosthesis is an artificial implant that is typically placed in a passageway or lumen in the body. Many endoprostheses are tubular members, of which examples include stents, stent-grafts, and covered stents.

[0003] Many endoprostheses can be delivered inside the body by a catheter. Typically
15 the catheter supports a reduced-size or compacted form of the endoprosthesis as it is transported to a desired site in the body, for example the site of weakening or occlusion in a body lumen. Upon reaching the desired site the endoprosthesis is installed so that it can contact the walls of the lumen.

[0004] One method of installation involves expanding the endoprosthesis. The expansion
20 mechanism used to install the endoprosthesis may include forcing it to expand radially. For example, the expansion can be achieved with a catheter that carries a balloon in conjunction with a balloon-expandable endoprosthesis reduced in size relative to its final form in the body. The balloon is inflated to deform and/or expand the endoprosthesis in order to fix it at a predetermined position in contact with the lumen wall. The balloon can then be deflated,
25 and the catheter withdrawn.

[0005] 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 reversible phase transition of its constituent material). Before and during introduction into the body until it reaches the desired implantation site, the endoprosthesis is restrained in a compacted
30 condition. Upon reaching the desired 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.

[0006] To support or keep a passageway open, endoprotheses are sometimes made of relatively strong materials, such as stainless steel or Nitinol (a nickel-titanium alloy), formed into struts or wires. The material from which an endoprosthesis is made can impact not only the way in which it is installed, but its lifetime and efficacy within the body.

SUMMARY

[0007] A method of making a support structure for a medical device, wherein the support structure has a shape, the method comprising: constructing a first layer of a first material by direct metal laser sintering, wherein the first layer has a shape that corresponds to the shape of the support structure; and introducing a first nitrogen content into a first part of the first layer by excimer laser nitriding.

[0008] A method of controlling disintegration of a medical device in an organism, comprising: constructing a support structure by building up alternating layers by direct metal laser sintering, and by excimer nitriding; and implanting the device into the organism, wherein the corrosion of the support structure occurs over a first period of time inside the organism.

[0009] A support structure for a medical device, wherein the support structure comprises alternating layers, wherein at least a first layer is formed by direct metal laser sintering, and at least a second layer, adjacent to the first layer, has a nitrogen content introduced into it by laser excimer nitriding.

[0010] A medical device for implantation into an organism, comprising: a support structure, wherein the support structure is configured to ensure steady biodisintegration thereof over a period of time inside the organism.

[0011] A method of using a medical device that comprises a support structure, wherein the support structure is biodisintegrable, the method comprising implanting the medical device in a body passageway of an organism.

[0012] The various details of one or more embodiments of the invention are set forth in the accompanying drawings and the description hereinbelow. Other aspects, features, and

advantages of the invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0013] FIGs. 1A – 1H and 1J – 1L are respectively, perspective views of exemplary endoprostheses.
- [0014] FIGs. 2A – 2D are respectively, perspective views of other exemplary endoprostheses.
- [0015] FIG. 3A shows a schematic diagram of a direct metal laser sintering apparatus. FIG. 3B shows the LENS apparatus.
- [0016] FIG. 4 is a graph of nitrogen content vs. nitrogen partial pressure, as employed in excimer nitriding.
- [0017] FIGS. 5A and 5B show a sequence of method steps in which layers of material are built up to form a support structure.
- [0018] FIG. 6 shows a layer having platinum nanoparticles.
- [0019] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

- [0020] Although endoprostheses have been highly effective at removing restrictions in body passageways, a number of problems have emerged that arise from their long-term placement. Restenosis is one; another is that, over time, microbes and other material can build up on a structure such as a stent and cause their own obstruction to free passage of body fluids through the lumen. Recently, there has been a move towards making endoprostheses out of bio-absorbable materials, such as magnesium, or iron alloys and biodegradable polymers, that ensure that the device structure naturally degrades over time. Alternatively, magnesium layers may be treated with HF to create layers of MgF. Such materials may, however, disintegrate too quickly for the useful life of an endoprosthesis — the mechanical performance of the endoprosthesis typically has to be maintained for at least three weeks — thus requiring endoprostheses to be made out of thicker elements than would be preferred. Uneven degradation is also a significant problem. Slight variations in a number of

uncontrollable environmental parameters such as temperature, fluid flow-rate, and local concentrations of critical agents, can cause a huge difference in the degradation course of different regions of exposed surface area. In many instances, the endoprosthesis disintegrates in a non-uniform manner, potentially releasing large fragments that can migrate and cause
5 boli and secondary blockages in narrower vessels at other locations.

[0021] Accordingly, the devices herein address such issues by making the support structures by processes, and from materials, that ensure that the support structures break down evenly across the entire structures, and over time, and significantly reduce the chance for large fragments being released.

10 *Definitions*

[0022] A biocompatible material is a material that can be introduced into living tissue or a living system, and is non-toxic or non-injurious to the tissue or system, and does not cause an immunological reaction or rejection in the concentrations in which it is deployed. The devices and methods described herein may be used with both materials that are biocompatible
15 and those that are not.

[0023] As used herein, a "biodisintegrable material" is a material that undergoes at least one of dissolution, degradation, absorption, erosion, corrosion, resorption, chemical transformation, or other disintegration processes over the period that a device formed at least in part from the biodisintegrable material is designed to reside in an organism. Chemical
20 transformation can include oxidation or other chemical reactions of the material. In some embodiments a biodisintegrable material is also biocompatible.

[0024] In specific embodiments, a biodisintegrable material is a material that exhibits substantial mass or density reduction by one or more of dissolution, degradation, absorption, erosion, corrosion, resorption, decomposition, degeneration, chemical transformation and/or
25 other disintegration processes after it is introduced into an organism. The disintegration occurs to a desirable extent in a timeframe that can provide a clinical benefit. Mass reduction of a biodisintegrable device can also occur, but in some cases does not occur, by fragmentation of the material. The disintegration can be the result of the chemical and biological interaction of the material with the physiological environment into which it is
30 implanted and/or can be initiated by applying a suitable triggering influence, such as a chemical reactant or source of energy to the device.

[0025] In some embodiments, a biodegradable material for use with the present invention exhibits substantial mass reduction after a period of time for which a function of the material, such as support of a lumen wall or delivery of a therapeutic agent in the immediate vicinity of the device, is no longer needed or desirable. By "a substantial
5 reduction" is meant that the biodegradable material exhibits a mass reduction through biodegradation of at least about 10%, at least about 20%, at least about 25%, at least about 30%, at least about 50%, at least about 75%, or at least about 90%, after a period of implantation. The period of implantation over which the mass reduction through
10 biodegradation takes place can be chosen to be one day or more, 14 days or more, 30 days or more, 60 days or more, 90 days or more, 180 days or more, 300 days or more, 600 days or more, or about 1,000 days or less. Thus, it would be understood that the level of biodegradability can be tailored to achieve a given level of mass reduction over a certain desired duration. For example, a medical device may be required to have reached a 75%
15 reduction in mass in 30 days. In another embodiment, it may be required to have attained a 30% reduction in mass in 180 days. It would also be understood by one of ordinary skill in the art that a period of days, such as 300 days, as used herein, entails a level of imprecision such that periods of 3–5 days either shorter or longer than the period in question are also acceptable equivalent timescales for measuring levels of biodegradability.

[0026] In certain embodiments of the present invention, only portions of the device
20 exhibit biodegradability. For example, an exterior layer or coating may be non-biodegradable, while an interior layer or body is biodegradable. It is also consistent with the methods and devices described herein that biodegradable elements are included within a polymeric matrix that is biostable (as defined hereinbelow), such that upon disintegration of the matrix, the device containing the matrix, such as a support structure, becomes less stiff.

25 [0027] A degradable material is a material that can dissociate, depolymerize, or otherwise reduce in molecular weight from its starting molecular weight, such that a resulting compound is soluble in an aqueous medium such as water or, if insoluble, can be suspended in a body fluid and transported away from an implantation site without obstructing the flow of the body fluid. A biodegradable material is one that will degrade into biocompatible
30 compounds as part of a biological process.

[0028] In some embodiments, a biodegradable material exhibits substantial mass reduction after a period of time for which a function of the material, such as support of a

lumen wall or delivery of a therapeutic agent in the immediate vicinity of the device, is no longer needed or desirable. By “a substantial reduction” is meant that the biodegradable material exhibits a mass reduction through biodegradation of at least about 10%, at least about 20%, at least about 25%, at least about 30%, at least about 50%, at least about 75%, or
5 at least about 90%, after a period of implantation. The period of implantation over which the mass reduction through biodegradation takes place can be chosen to be one day or more, 14 days or more, 30 days or more, 60 days or more, 90 days or more, 180 days or more, 300 days or more, 600 days or more, or about 1,000 days or less. Thus, it would be understood that the level of biodegradability can be tailored to achieve a given level of mass reduction
10 over a certain desired duration. For example, a material may be required to have reached a 25% reduction in mass in 600 days. In another embodiment, it may be required to have attained a 30% reduction in mass in 300 days. It would also be understood by one of ordinary skill in the art that a period of days, such as 180 days, as used herein, entails a level of imprecision such that periods of 3–5 days either shorter or longer than the period in
15 question are also acceptable equivalent timescales for measuring levels of biodegradability.

[0029] A resorbable material is a material that is soluble, biodisintegrable as defined herein, or is an aggregate of soluble and/or disintegrable material(s) with insoluble material(s) such that, with the resorption of the soluble and/or disintegrable materials, the residual insoluble materials are of sufficiently fine size that they can be suspended in a body
20 fluid and transported away from the implantation site without obstructing the flow of the body fluid. Ultimately, the particles are eliminated from the body either by excretion in fluids such as perspiration, urine or feces, or are themselves dissolved, degraded, corroded or otherwise metabolized into soluble components that are then excreted from the body. A bioresorbable material is a resorbable material that is biocompatible.

25 [0030] In certain embodiments, as further described herein, biostable materials, *e.g.*, polyelectrolytes, may be utilized. As used herein, a “biostable material” is a material that does not undergo substantial dissolution, degradation, absorption, erosion, decomposition, corrosion, chemical transformation, resorption and/or other disintegration processes over the period that the material is designed to reside in an organism.

30 [0031] The term “body fluid” as used herein refers to fluids in the body of an organism — especially a mammal — including, but not limited to, blood, urine, saliva, lymph, plasma, gastric, biliary, or intestinal fluids, seminal fluids, and mucosal fluids or humors.

[0032] The terms “therapeutic agent”, “pharmaceutically active agent”, “pharmaceutically active material”, “pharmaceutically active ingredient”, “drug” and other related terms may be used interchangeably herein and include, but are not limited to, small organic molecules, peptides, oligopeptides, proteins, nucleic acids, oligonucleotides, genetic therapeutic agents, non-genetic therapeutic agents, vectors for delivery of genetic therapeutic agents, cells, and therapeutic agents identified as candidates for vascular treatment regimens, for example, as agents targeting restenosis.

[0033] By small organic molecule is meant an organic molecule having 50 or fewer carbon atoms, and fewer than 100 non-hydrogen atoms in total.

10 [0034] As used herein, an “antimicrobial agent” is any agent that is harmful to microbes, especially pathogenic bacteria.

[0035] As used herein, “treatment” includes an amelioration of a disease or condition, including the prevention of a disease or condition, the reduction or elimination of symptoms associated with a disease or condition, or the substantial or complete elimination of a disease or condition.

Overview

[0036] Medical devices having a mechanical support structure that has controllable biodisintegrability, and methods of making the devices, are disclosed.

20 [0037] The support structure of the medical device can be generally tubular in shape and can be a part of a stent. Endoprostheses such as stents come in a variety of shapes. Simple tubular structures having a single tube, or with complex structures, such as branched tubular structures, can be used.

[0038] Devices, such as stents, may be formed from many known constructions such as cross-hatched or mesh filaments or interlocking loops. Almost all have a complex and delicate structure that permits them to deform in a manner necessary for implantation, as well as to be inflated into the configuration that they adopt *in situ*. Exemplary stents 10 having a lattice, or cage-like, framework are shown in FIGs. 1A – 1H and 1J – 1L. The structures in FIGs. 1A – 1C, and 1E – 1L are all made of a single piece of metal. The structure in FIG. 1D is made of a helically wound wire 4, and may comprise several interlocking pieces, arranged in a wave-like configuration 12 and having gaps 5.

[0039] In FIG. 1A, 12 is a control wire used while coating stent 10. Preferred configurations for the stent of FIG. 1D are described in U.S. Patent Application Publication No. 2004/0181278, September 16, 2004. FIG. 1E shows an expandable and deformable tubular stent, as described in U.S. Patent No. 4,733,665. Longitudinal struts 31 are connected to one another by one or more tabs 34, which serve to define one or more slots 32, and spaces 35. In FIG. 1F, stent 10 is constructed from wire-like members 12, bent into serpentine configurations 12, 14, 16, and connected to one another by interconnecting members 20, as further described in U.S. Patent Application Publication No. 2001/0032014, October 18, 2001. In FIG. 1G, a further stent embodiment 10 has wire members 112 configured into a rectangular mesh having gaps 122 at the ends, and enclosed spaces 116 in the middle. FIG. 1H shows a further embodiment of a stent in which wire members 12 are configured to enclose irregular shaped gaps 16, and where wire members 12 are coated with a polymer layer 30. In FIG. 1J, wires 22 are configured into a zig-zag arrangement, linked to one another with interconnecting members 24.

[0040] The devices of FIGs. 1K and 1L are designed to cover a region of a lumen having a side-branch.

[0041] As can be seen from all of the devices of FIGs. 1A – 1H and 1J – 1L, the structures are formed from a number of members, sometimes fused to one another. The various members, often called struts, are made from thin portions of material. The dimensions of a given strut are typically in the range 0.1 – 2.0 mm in width and thickness, and 1.0 – 5.0 mm in length.

[0042] Still other exemplary endoprostheses are tubular grafts, as depicted in FIGs. 2A – 2D. Such endoprostheses are made from cylindrical sheets, either extruded as a single tubular sheet 202, as in FIGs. 2B – 2D, or extruded as a single sheet 200, open at its edges but configured such that it can expand or contract in radius to fit within a given lumen, as in FIG. 2A. Each of the devices in FIGs. 2A – 2D can have one or more materials of a different composition attached to its surface, as shown in FIGs. 2B – 2D. It is assumed that, as used in this regard, the term “attached” can mean “affixed”, “grafted on”, “deposited on”, “engraved on”, “embedded in”, and other similar terms.

[0043] There are two principal aspects to controlling the disintegration rate of bio-disintegrable endoprostheses. First, as would be appreciated by one of ordinary skill in the

art, a temporary delay of the onset of biodisintegration is helpful in maintaining the mechanical integrity of the device while it is being covered with endothelial cells. Second, there are situations in which it is desirable to be able to fully control the corrosion over the entire lifespan of the device, even if 80% of the material has already been removed. This latter scenario particularly applies where parts of a device will never be fully covered with endothelial cells (for example with a strut passing over a side-branch). In such circumstances, it is important that the exposed strut does not break until the very core of the support structure has degraded. A very slow final corrosion of the center of the strut would therefore be helpful in such a configuration.

10 [0044] The disintegration rate of a medical device can be delayed by various surface treatments or surface coatings as is known in the art. However, such approaches do not permit control over disintegration of the support structure once the surface coatings have dissipated.

[0045] The overall disintegration rate of the bulk support structure can be controlled by tailoring the material, *e.g.*, an alloy, from which it is made. However, where the structure is made from a homogeneous composition, this leads only to a single degree of freedom in controlling rate of disintegration.

[0046] No method has yet been proposed which allows the disintegration rate to be designed truly in all three dimensions of a support structure. For example, where the disintegration rate is an increasing function towards the core so that a much slower rate is followed at the final inner core, the device is thereby permitted to become a thin durable skeleton that does not disintegrate too early in the life of the device.

[0047] Control of device disintegration rate in three dimensions is achieved by making the device from one or more of several processes, as further described herein. The first process is referred to as direct metal laser sintering (DMLS); a specific example is known as laser-engineered net shaping (LENS). These processes permit control of the composition and properties of the structure at various places therein, as it is being manufactured, for example by changing the composition of the metal as it is being build up. Thus, different layers or materials at different positions along the device have different powder compositions. A second process, excimer laser nitriding, permits introduction of variable quantities of nitrogen atoms into a layer of material as it is being deposited. Nitrogen mixed with certain metals

can profoundly influence their electrical and mechanical properties according to its proportion. Furthermore, instead of, or in addition to, laser nitriding, an unfinished device can be treated by, for example dipping it into hydrofluoric acid, thereby converting magnesium into magnesium fluoride. The latter is much more resistant to corrosion than is
5 magnesium. Combinations of the foregoing methods may be used. For example, as a LENS process is used to build up a device, layer after layer, any surface treating process described herein – or known to one of ordinary skill in the art – can be applied in between layers to the partly finished device.

DMLS

10 [0048] Direct metal laser sintering (DMLS), and Laser Engineered Net Shaping (LENS), make near-net-shaped (*i.e.*, having a desired end-product shape) metal parts directly from three-dimensional computer-aided design (3D CAD) models. See, *e.g.*, J. Hänninen, “Direct Metal Laser Sintering”, *Advanced Materials & Processes*, 160:33-36, (2002), incorporated herein by reference. A strength of these technologies lies in the ability to fabricate fully-
15 dense metal parts with good metallurgical properties at reasonable speeds. “Fully dense” means that the density of the metal part being made is as good as that of a structure being made, starting from bulk material, and that no voids or bubbles get incorporated into the produced material. Accordingly, the mechanical properties of the resulting part are virtually identical to conventionally made products. Material composition can be changed
20 dynamically and continuously, leading to objects with properties that might not be possible using classical fabrication methods. DMLS has fewer limitations than selective laser sintering (SLS) in terms of available materials. DMLS has been widely deployed in the fabrication and repair of injection molding tools, and in the fabrication of large titanium and other exotic metal parts for aerospace applications. In short, objects fabricated with DMLS
25 are near net shape, but generally will require finish machining. They are fully-dense with good grain structure, and have properties similar to, or even better than the intrinsic materials.

[0049] A schematic view of an apparatus for carrying out LENS is shown in FIG. 3A. The apparatus is usually contained within a chamber, both to isolate the process from the ambient surroundings and to shield the operators from possible exposure to fine powders and
30 the laser beam.

[0050] During operation of a LENS apparatus, a high power laser 300 is used to melt metal powder 310 supplied coaxially to the focus of the laser beam through a deposition head

320. The laser power used varies greatly, from a few hundred watts to 20 kW or more, depending on the particular material, feed-rate and other parameters. The laser beam typically travels through the center of the head and is focused to a small spot on a substrate 330 by one or more lenses 340. Substrate 330 rests upon a X-Y table 350, which is moved, for example in raster fashion, to fabricate each layer of the object. Motions of table 350 are controlled by CPU 360, typically under instructions from a CAD program. Normally the head is moved up vertically, in the z-direction as depicted in FIG. 3A, as each layer is completed. A rotating axis can also be easily implemented, thereby allowing structures having tubular shapes to be processed. Layer thickness varies with the material being deposited, but the thickness is typically in the range 20 – 50 μm . In alternate embodiments, the head is stationary and the object on the table is moved in a vertical direction. By depositing a metal in a layer-by-layer process, LENS produces fully dense parts with material properties that are comparable to, or better than, those of wrought materials.

[0051] The laser beam may be delivered to the substrate by any convenient means. A simple right angle mirror 370 is shown in FIG. 3A, but fiber optics can also be used. Metal powders 310 are delivered and distributed around the circumference of the head either by gravity, or by using pressurized carrier gas 380. Typically carrier gas 380 is an inert gas such as helium, neon, krypton, argon, xenon, or a gas that does not react under the DMLS conditions, such as nitrogen, or carbon dioxide. Even in cases where a gas is not required for feeding, an inert shroud gas 390 is typically used to shield the melt pool from atmospheric oxygen for better control of properties, and to promote layer to layer adhesion by providing better surface wetting.

[0052] Most systems use powder feedstocks, but material provided as fine wires has also been used, in which case the material is fed off-axis to the beam.

[0053] In another variation of the method, as depicted in FIG. 3B, a high-powered, focused, Nd:YAG laser beam first strikes a tiny spot on a metal substrate, thereby producing a molten pool. Other lasers, known in the art, are also capable of carrying out the method. A nearby nozzle blows a precise amount of metal powder into the pool to increase the material volume. The working head moves back-and-forth, line by line, overlapping each layer of metal on the substrate, under control of a computer processor. Repeating this process, layer by layer, produces a metal version of the CAD model.

[0054] An overview of DMSL is provided in: "Direct Metal Laser Sintering for Rapid Tooling: Processing and Characterization of EOS Parts", M. W. Khiang, *et al.*, J. Materials Proc. Technol., 113, 269-272, (2001), incorporated herein by reference. Other variants of DMLS, suitable for use with the methods and devices described herein are found in:

- 5 "Formation Method for New Corrosion-Resistance [sic] Magnesium Thin Film by CVD Method", M. H. Lee, *et al.*, *Surface and Coatings Technology*, 169-170, 670-674, (2003), and "Thermal and Mechanical Finite Element Modeling of Laser Forming from Metal and Ceramic Powders", K. Dai and L. Shaw, *Acta Materialia*, 52, 69-80, (2004), both of which are incorporated herein by reference. Various methods of carrying out DMLS are described
- 10 and compared in F. Erzincanli and M. Ermurat, "Comparison of the Direct Metal Laser Fabrication Technologies", 2nd International conference on Responsive Manufacturing, University of Gaziantep, Turkey, (2002), also incorporated herein by reference.

[0055] DMLS differs from LENS as depicted in FIG. 3A principally in that the powder is deposited as a layer over the substrate by a coating element, instead of through a concentric

15 feed around the laser beam. In DMLS, then, the laser beam is directed through successive x-y motions across the substrate and, wherever it contacts the powder, melts the powder, fusing it to the layers below. Excess powder is removed, and successive layers are built up by recoating the immediately previous deposited layer with further layers of powder. By contrast, in LENS, the laser melts the stream of powdered metal as it is deposited.

- 20 [0056] DMLS and LENS increase a designer's choice of materials. A variety of materials, such as stainless steel, inconel, copper, and aluminum, can be used. Typically the powders are carefully tailored to balance the shrinkage that takes place during sintering by the expansion of the individual powder particles. Of particular interest are reactive or hard-to-machine materials such as titanium. Titanium poses few difficulties for DMLS because
- 25 DMLS makes structures by depositing metal powders. Even multiple powders can be fused in different combinations to create parts that were once impractical, prohibitively expensive, or both. The process gradually transitions between different materials to reduce stress at the interface. The capabilities let designers specify different materials for different areas of a part, depending on the requirements of each.

30 *Excimer Laser Nitriding*

[0057] Excimer laser nitriding can be used to form nitrides of various metals, including iron, steel, aluminum, titanium, magnesium, and alloys thereof. For example, magnesium-

nitride can be created in the surface of a magnesium target by irradiating the substrate with an excimer laser in a molecular nitrogen environment. The laser pulse melts the magnesium target on contact, and creates nitrogen ions in the plasma just above the substrate. These ions react with the magnesium molten by the laser pulse. Magnesium nitride is an excellent protector against corrosion. Exemplary conditions for excimer laser nitriding are described in Soto, G., *et al.*, "Amorphous magnesium nitride films produced by reactive pulsed laser deposition", *J. Non-Crystalline Solids*, 342:65–69, (2004).

[0058] Representative excimer lasers for use in excimer nitriding include, but are not limited to, the XeCl, KrF and ArF excimer lasers. The layer thicknesses that can be constructed in this way are in the range 1 – 10 μm , and preferably 2 – 7 μm , and even more preferably 3 – 5 μm .

[0059] The nitrogen content of magnesium nitride formed by excimer nitriding, given by $x = [\text{N}]/[\text{Mg}]$ (where square brackets denote atomic concentrations), changes between 0 and 0.73 for a corresponding variation in nitrogen pressure of 4×10^{-10} Torr to 60 mTorr. By this method it is possible to achieve sub-, over- and stoichiometric films at different nitrogen pressures. FIG. 4 shows a graph of nitrogen content vs. nitrogen partial pressure, as employed in excimer nitriding. The graph demonstrates the ability to tailor the nitriding level by adjusting the gas pressure. Ablation was accomplished by means of a KrF excimer laser ($\lambda = 248$ nm) focused on the target at 50° off the surface normal. Laser energy, number of pulses and pulse repetition rate were fixed at 400 mJ, 3800 pulses and 2 Hz, respectively, with a laser energy density at target surface of 5 J cm^{-2} . The results show that the amorphous matrix keeps its metallic character for $x < 0.45$; $x = 0.4$ is a critical composition at which the material starts developing ionic characteristics; at $x = 0.66$ the solid is totally ionic.

[0060] It has been observed that the metallic nature of magnesium disappears when the nitrogen content, $x = [\text{N}]/[\text{Mg}]$, gets above $x > 0.4$. In other words, building a 3D structure utilizing both the layer-by-layer DMSL process with alternating excimer nitriding steps, producing $x > 0.4$ throughout the entire strut will create non-metallic struts. So, building in a couple of small sections throughout the circumference of the support structure will result in a stent that allows structure internal to it to be visible in an MRI scan, which is desirable for medical imaging.

[0061] The atomic concentration can also be influenced by the number of laser pulses used in the excimer nitriding process, and their duration. As the depth of the nitriding effect depends on the diffusion length during the molten state of the magnesium, pulse length and number does permit this property to be adjusted. Excimer lasers can of course be

- 5 programmed to deliver exact amount of pulses in controllable energy fluence per pulse. Factors affecting the efficacy of laser nitriding are described in: M. Han, "Laser nitriding of metals", Ph.D. thesis, University of Göttingen, (2001), incorporated herein by reference.

Methods of Manufacture

- [0062] Medical devices of the present invention can be made by processes that alternate the layer by layer DMSL build up of a metallic structure of, *e.g.*, magnesium or iron, with excimer laser treatment to build in a certain nitride level in the layer deposited immediately previously. Metallic structures may also incorporate other metals. For example, if only part of a stent is supposed to disappear, then noble metals such as titanium, tantalum, or gold can be combined as one or more of the layers in the same device with erodible metals such as
- 15 magnesium or iron. A totally non-bioerodible device can therefore be made with this technology by integrating heavily nitrided sections within the metal structure. The resulting structure can be, *e.g.*, a MRI-compatible stent. A schematic of the process is shown in FIG. 5. The laser nitriding is optional for each layer. It is also not necessary to treat the whole cross-section of the layer by the nitriding process as the laser beam can be focused onto a
- 20 much smaller portion (as shown in FIG. 5). Such precision permits tailoring of disintegration rates of different parts of the devices.

- [0063] FIG. 5A shows a flow-chart of steps associated with build-up of multiple layers of material, and corresponding schematic representation of the layers. At step 500, a first layer 501 is deposited with a DMSL technique such as LENS. Since the shape in which the first
- 25 layer is deposited will determine the overall shape of the device, it is desirable to control the shape of the first layer. Several ways of defining a shape for the first layer are available. By starting with a flat substrate, a first structure, such as a thin tube in the shape of a stent, can be built perpendicular to the surface. Subsequently, if the structure is a thin tube, it can be rotated by 90 degrees so that its axis lies parallel to the substrate, and the further layers can be
- 30 deposited as further described hereinbelow while rotating the tube about its axis. Although this manner of defining a first layer creates a solid tube without any pattern as is normally found in, *e.g.*, a stent, after cutting the tube from the substrate a stent pattern can easily be

laser cut into the tube, according to methods known to one of ordinary skill in the art. In an alternative embodiment of defining a shape on which a first layer is deposited, a silica base shape (*e.g.*, a wire) can be used. Silica is an effective choice because it can withstand temperatures of up to around 1000 °C as are encountered during, *e.g.*, DMLS or excimer
5 nitriding and so a molten metal can be deposited directly on the silica base shape. After the device has been completed, the silica can be dissolved in hydrofluoric acid. Although hydrofluoric acid will also react with any magnesium in the structure, this reaction only forms a MgF₂ layer on the outer surface of the magnesium.

[0064] Subsequently, step 510 excimer nitriding is applied to first layer 500, to create a
10 first nitride layer 511, having a first nitrogen content. A second layer 521 is deposited on the first nitride layer 511, in step 520, using a DMSL technique. It is preferable, though not necessary, to use the same DMSL technique for the second and subsequent layers as for the first layer. It is also preferable that the material used in the second and subsequent layers is the same as the material used in the first layer, though this does not necessarily have to be the
15 case, particularly where a graduation of properties is desired to be achieved in a manner other than by introducing nitrogen content in various layers. In step 530, excimer nitriding is applied to second layer 521 to create a second nitride layer 531 having a second nitrogen content. It is to be understood that step 530 can be omitted so that the second layer is given no nitride content. The second nitride content need not be the same as the first nitride content
20 in the first nitride layer. In a further step 540, a third layer 541 is deposited with DMSL on top of the second nitride layer. As shown in FIG. 5, the third layer is not given any nitride content by excimer nitriding, though as would be understood by one of ordinary skill in the art, the third layer could receive a third nitride content as desired. In step 550, a fourth layer 551 is deposited on the third layer. In step 560 excimer nitriding is applied to layer 551 to
25 produce a nitride layer 561. The steps 500 – 560 can be repeated to cause build up of multiple layers, either consecutively having nitride content, or in some sequences, alternating layers having nitride content with layers having no nitride content.

[0065] FIG. 5B shows a flow-chart analogous to that shown in FIG. 5A but illustrating how nitrogen content can be selectively introduced into parts of various layers. Step 502, in
30 which a first layer of material 504 is deposited by a DMSL method such as LENS, is analogous to step 500 of FIG. 5B. In step 512, however, excimer nitriding is applied only to a part of first layer 504, thereby creating a region 514 having a desired first nitrogen content.

The region may be defined by applying a removable mask, or by other methods familiar to one of ordinary skill in the art of deposition technologies. In step 522, a second layer 524 is deposited over the first layer 504 by a DMSL method. In step 532, excimer nitriding is applied to second layer 524 to create, in the instance shown, two regions having nitrogen content. Steps 502 – 532 can be repeated to build up a structure of desired shape and cross-section 592, as shown, in which regions 594 and 596 have nitrogen content, that need not be identical to one another. Such a construct can be used to make structures such as stent struts which, if desired, can have different properties from the rest of the device around them.

[0066] Layers of the multi-layer structure made in this way may have the same thickness as one another or different thicknesses. In some embodiments, an individual layer and/or an individual layer may have a thickness of at least about 1.0 micron (*e.g.*, at least about 5.0 microns, at least about 10 microns, at least about 50 microns, at least about 100 microns, at least about 300 microns), and/or at most about 500 microns (*e.g.*, at most about 300 microns, at most about 100 microns, at most about 50 microns, at most about 10 microns, or at most about five microns). For example the commercially available EOS 270 M permits a minimum layer thickness of 20 micrometer. Another commercially available piece of equipment, the M 250, can create layers as small as 50 micrometer.

[0067] One can build a structure with the DMSL process in which it is possible to change metal composition in any of three orthogonal directions (*e.g.*, as represented by a cartesian *x*, *y* and *z* axis system) just by choosing an appropriate mixture of metal powders at each instant. It is also possible to provide an additional controlled nitriding treatment throughout the complete bulk by using excimer nitriding. Different powders can be applied simultaneously and it is important to note that not all of the powders have to melt to create a structure. It is possible to, for example, blend in platinum (or iron) nano-particles with a very high melting point in a magnesium matrix by feeding both materials at the same time into the laser focus, as shown in FIG. 6. The magnesium will melt, thereby fusing with the bulk and incorporating the platinum nano-particles during the solidification. Incorporation of, *e.g.*, platinum, nanoparticles will locally allow acceleration of the disintegration rate by means of a galvanic cell which is created once the platinum particle is exposed to a saline environment.

[0068] This thereby demonstrates that it is possible to both accelerate as well as delay the disintegration rate of the support structure by varying the application of the DMSL and the excimer laser process.

[0069] Furthermore, it is possible to start with a structure such as a semi-stent, i.e., an unfinished stent such as one that has not been finished with electro-polishing, made by a different technology (such as cutting a pattern in a tube by laser) and to add to this structure material by means of the DMSL process. It is also possible to apply the LENS processes described herein to a finished stent, thereby permitting build up of additional layers. Such approaches might be advantageous to speed up the overall production process because it thereby avoids using a sacrificial, dissolvable, mandrel. An option is to start with a very thin stainless steel skeleton, plate a first magnesium layer on top of this, e.g., by magnetron sputtering (see, e.g., M. H. Lee, *et al.*, *Surface and Coatings Technology*, 169–170, 670–674, (2003)) and build up further layers by means of DMSL. This also permits intermediate layers between the LENS made layers to be created, and sputtering permits deposition of layers whose thicknesses are in the submicron range.

[0070] This approach described herein also makes it possible to join different structures together by building an axial connector that erodes after placement *in vivo*. For example, a stent for placement in a limb such as a leg, where very high repetitive binding of the arteries occurs, consists of a series of nitinol rings connected by magnesium axial connectors, in order to make sure that disintegration starts in the middle of the connectors and works towards the nitinol rings, it is sufficient to refine the excimer nitriding process to deliver a low number of pulses in the middle, gradually increasing to a high number of pulses near the nitinol rings. In this embodiment, the magnesium connectors support the stent during the first few weeks of placement to keep the vessel open, but once the stent is endothelialized, less support is needed and the rings are sufficient, allowing the artery to bend much better.

[0071] Many embodiments of a medical device having different numbers of layers in one portion from another portion are possible. By “portion” is meant some non-vanishing part that is less than the whole. Thus, in some embodiments, one portion of a medical device comprises a multi-layered structure with at least 5 layers (e.g., at least 10 layers, at least 20 layers, at least 30 layers, or at least 40 layers), and another portion of a medical device includes a multi-layered structure with at least 20 layers (e.g., at least 30 layers, at least 40 layers, or at least 50 layers). For example, one portion of a medical device may include a

multi-layered structure with 10 layers and another portion of the medical device may include a multi-layered structure with 40 layers. In certain embodiments, a multi-layered structure in one portion of a medical device can include from five to 50 layers (e.g., from 10 to 30 layers) more than a multi-layered structure in another portion of the medical device.

5 [0072] In some embodiments, the biodisintegrable material in a portion of the underlying structure that is made up from a relatively large number of layers may begin to disintegrate after, and/or more slowly than, the biodisintegrable material in a portion that includes a relatively small number of layers. Thus, the numbers of layers of a support structure may be used to provide different disintegration rates of biodisintegrable material in different regions
10 of the medical device. In some embodiments, an endoprosthesis can include an arrangement of layers that causes one or both of the ends of the endoprosthesis to start disintegrating before the middle of the endoprosthesis. This may limit the likelihood of the medical device breaking apart into two or more pieces during disintegration.

[0073] In some embodiments, one or more portions of a medical device are not
15 constructed, layer-by-layer at all.

Delivery of therapeutic agents

[0074] In some embodiments, the device is further configured to deliver one or more therapeutic agents. As an example, one or more therapeutic agents can be disposed on or within the multi-layered structure that coats the device, thereby giving the medical device a
20 drug releasing function upon implantation. Therapeutic agents may be used singly or in combination. It is also possible, for example, to make a porous outer layer of a stent from magnesium and then to dip the stent into a solution containing the therapeutic agent in order to load the drug into the pores. An example of such a pore structure is given in M. H. Lee, *et al.*, *Surface and Coatings Technology*, 169–170, 670–674, (2003), at Figure 1.

25 [0075] Examples of therapeutic agents can be found at cols. 4 – 6 of U.S. Patent No. 6,899,731 to Li *et al.*, and at cols. 5 – 8 of U.S. Patent No. 6,923,996 to Epstein *et al.*, the disclosures of which are incorporated by reference in their entirety. It is to be understood that the therapeutic agents that can be used are not limited to those found herein.

[0076] Examples of therapeutic agents and methods of incorporating such agents into a
30 multi-layer structure are described in U.S. Patent Application No. 10/849,742, filed May 20,

2004. U.S. Patent No. 5,733,925, to Kunz *et al.*, also provides general guidance for incorporating therapeutic agents into layers.

[0077] The multi-layer structure may instead or additionally be used to deliver an antimicrobial agent, such as for the purpose of preventing or limiting local infection in the vicinity of the device. Exemplary antimicrobial agents have broad-spectrum activity and include triclosan, chlorhexidine, silver sulfadiazine, silver ions, benzalkonium chloride, and zinc pyrithione, as well as broad-spectrum antibiotics such as quinolones, fluoroquinolones, aminoglycosides and sulfonamides. Antiseptics such as iodine, methenamine, nitrofurantoin, validixic acid and other acidifying agents, including acids extracted from cranberry juice may also be used.

[0078] The therapeutic agent can be charged, either because it is itself a charged molecule or because it becomes charged upon, for example, a change in ambient pH or upon association with a charged species. Examples of charged therapeutic agents include small molecule and polymeric therapeutic agents containing ionically dissociable groups. In some embodiments in which the therapeutic agent does not possess one or more charged groups, it can nevertheless be provided with a charge, for example, through non-covalent association with a charged species. Examples of non-covalent associations include hydrogen bonding, electrostatic, van der Waals, and hydrophobic/lipophilic interactions. For instance, a therapeutic agent can be associated with an ionic amphiphilic substance.

[0079] A wide range of therapeutic agent loadings can be used. The amount of such loading can be readily determined by those of ordinary skill in the art, and will ultimately depend upon the condition to be treated, the nature of the therapeutic agent itself, the avenue by which the therapeutic-agent-loaded layer-by-layer structure is administered to the intended subject, and so forth. The loaded multi-layered structure, may comprise, for example, from about 1 wt. % to about 70 wt. % therapeutic agent.

[0080] The amount of the therapeutic agent may be limited by the propensity of such agent to cause an undesirable localized or systemic toxic reaction and by the impairment of mechanical properties necessary for proper functioning of the device.

[0081] In still other embodiments, the therapeutic agent can be provided within charged nanocapsules, which are formed, for example, using methods such as those described in U.S. Patent Application Publication No. 2005-0129727, entitled "Localized Drug Delivery Using

Drug-Loaded Nanocapsules". In such embodiments, one or more layers of charged nanocapsules can be deposited during the course of assembling the multi-layer coating.

[0082] In still other embodiments, the multi-layer structure is loaded with a therapeutic agent subsequent to its formation. For example, the porosity, and thus the permeability, of the multi-layer structure can be modified by adjusting the pH exposed to the structure, as described, for example, in Antipov, A. A., *et al.*, "Polyelectrolyte multilayer capsule permeability control," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 198-200, 535-541, (2002). A porous layer can absorb a therapeutic agent after the layer is in place.

10 *Device materials*

[0083] The support structure of the medical device of the present invention is, in some embodiments, formed of a biocompatible material, such as the materials described herein. Specific examples of biocompatible materials from which the underlying structure can be formed are described in U.S. patent application serial no. 10/440,063, filed May 15, 2003; and U.S. Patent Application Publication Nos. 2003-0018380, 2002-0144757, and 2003-0077200. Still further examples of biocompatible materials are described, for example, in Weber *et al.*, U.S. Patent Application Publication No. 2004/0230290 A1, published on November 18, 2004; Craig *et al.*, U.S. Patent Application Publication No. 2003/0018380 A1, published on January 23, 2003; Craig *et al.*, U.S. Patent Application Publication No. US 2002/0144757 A1, published on October 10, 2002; and Craig *et al.*, U.S. Patent Application Publication No. 2003/0077200 A1, published on April 24, 2003. Preferred materials suitable for DMLS/laser nitriding are materials that can be molten. Into a molten pool of material can be sprayed both metallic or ceramic powders or even a combination thereof. It is also possible to spray a mixture of magnesium and magnesium-nitride powders to achieve a similar effect to the laser nitriding process.

[0084] The biocompatible material can be suitable for use in, for example, a balloon-expandable stent, a self-expandable stent, or a combination of both (see *e.g.*, U.S. Patent No. 5,366,504). A self-expandable stent can be formed of a continuous solid mass of a relatively elastic biocompatible material, such as a superelastic or pseudo-elastic metal alloy, for example, a Nitinol (*e.g.*, 55% nickel, 45% titanium). A self-expanding stent has a mechanical memory such that it can return to a preformed shape after it has been compressed or deformed. The stent is initially configured in its final desired shape and is then contracted by

deforming or constraining it using any of several methods known in the art. It remains in a contracted state until it is delivered to the target site where it is allowed to expand to its initial state. Examples of materials that can be used for a balloon-expandable stent include noble metals, radiopaque materials, stainless steel, and alloys comprising stainless steel and one or
5 more radiopaque materials.

[0085] The support structure can be formed of a biodegradable material, such as a biodegradable metal, or a biodegradable metal alloy. Biodegradable materials are described, for example, in U.S. Patent No. 6,287,332 to Bolz; U.S. Patent Application Publication No. US 2002/0004060 A1 to Heublein; U.S. Patent Nos. 5,587,507 and 6,475,477
10 to Kohn *et al.* Examples of biodegradable metals for use with the support structure include alkali metals, alkaline earth metals (*e.g.*, magnesium), iron, zinc, and aluminum. Examples of biodegradable metal alloys include alkali metal alloys, alkaline earth metal alloys (*e.g.*, magnesium alloys), iron alloys (*e.g.*, alloys including iron and up to seven percent carbon), zinc alloys, and aluminum alloys.

15 [0086] In some embodiments, a biodegradable material from which the underlying structure is formed, can include at least one metallic component and at least one non-metallic component, or at least two different metallic components. In some embodiments, a biodegradable material can include at least one of the following: manganese, cobalt, nickel, chromium, copper, cadmium, lead, tin, thorium, zirconium, silver, gold, palladium, platinum,
20 rhenium, silicon, calcium, lithium, aluminum, zinc, iron, carbon, and sulfur. In certain embodiments, a biodegradable material can include at least two of the following metals in proportions by weight of greater than about 1%: magnesium, titanium, zirconium, niobium, tantalum, zinc, or silicon, and lithium, sodium, potassium, calcium, iron, or manganese. In certain embodiments, the biodegradable material can include a first component selected
25 from the group consisting of: magnesium, titanium, zirconium, niobium, tantalum, zinc, silicon, and another, different, component selected from the group consisting of: lithium, sodium, potassium, calcium, iron, manganese.

[0087] The properties of the support structure depend upon the material from which it is formed. Magnesium, for example, has a relatively low mass attenuation factor, and the CT
30 visibility of the region (*e.g.*, a body lumen) in which a magnesium structure is located can be relatively high.

[0088] Metallic materials from which the underlying structure is made may be made into filaments and then woven so that the underlying structure forms a regular network of metal mesh. If the network is made of metal, the intersection between different filaments may be formed by welding, twisting, bending, gluing, tying (with suture), heat sealing, or by any other manner known in the art.

[0089] As another example, the support structure of a medical device can include one or more biostable materials in addition to including one or more biodisintegrable materials. One or more polymers may be used (as described herein) to control the disintegration of one or more of the biodisintegrable regions of the stent. The polymers may be in the form of layers over the biodisintegrable and/or biostable regions of the stent or a fiber meshwork similarly disposed. Examples of biostable materials include stainless steel, tantalum, nickel-chrome, cobalt-chromium alloys such as Elgiloy® and Phynox®, Nitinol (e.g., 55% nickel, 45% titanium), and other alloys based on titanium, including nickel titanium alloys, thermo-memory alloy materials. Stents including biostable and biodisintegrable regions are described, for example, in U.S. Patent Application Serial No. 11/004,009, filed on December 3, 2004, and entitled "Medical Devices and Methods of Making the Same".

Stents/Devices

[0090] The embodiments described herein may be used in conjunction with various medical devices, in particular endoprostheses. Exemplary medical devices are implantable or insertable medical devices, including catheters (for example, urinary catheters or vascular catheters such as balloon catheters), guide wires, balloons, filters (e.g., vena cava filters), stents of any desired shape and size (including coronary vascular stents, aortic stents, cerebral stents, urology stents such as urethral stents and ureteral stents, biliary stents, tracheal stents, gastrointestinal stents, peripheral vascular stents, neurology stents and esophageal stents), grafts such as stent grafts and vascular grafts, cerebral aneurysm filler coils (including GDC-Guglielmi detachable coils-and metal coils), filters, myocardial plugs, patches, pacemakers and pacemaker leads, heart valves, and biopsy devices. Indeed, embodiments herein can be suitably used with any metallic support structure which is designed for use in a patient, either for procedural use or as an implant.

[0091] The medical devices may further include drug delivery medical devices for systemic treatment, or for treatment of any mammalian tissue or organ. Subjects can be mammalian subjects, such as human subjects. Non-limiting examples of tissues and organs

for treatment include the heart, coronary or peripheral vascular system, lungs, trachea, esophagus, brain, liver, kidney, bladder, urethra and ureters, eye, intestines, stomach, colon, pancreas, ovary, prostate, gastrointestinal tract, biliary tract, urinary tract, skeletal muscle, smooth muscle, breast, cartilage, and bone.

- 5 [0092] In some embodiments, the medical device is used to temporarily treat a subject without permanently remaining in the body of the subject. For example, in some embodiments, the medical device can be used for a certain period of time (e.g., to support a lumen of a subject), and then can disintegrate after that period of time.

- 10 [0093] Depending on specific application, stents can have a diameter of between, for example, 1 mm and 46 mm. In certain embodiments, a coronary stent can have an expanded diameter of from about 2 mm to about 6 mm. In some embodiments, a peripheral stent can have an expanded diameter of from about 4 mm to about 24 mm. In certain embodiments, a gastrointestinal and/or urology stent can have an expanded diameter of from about 6 mm to about 30 mm. In some embodiments, a neurology stent can have an expanded diameter of
15 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.

- [0094] Stents can also be a part of a stent-graft or a covered stent. In other embodiments, stents can include and/or be attached to a biocompatible, non-porous or semi-porous polymer
20 matrix made of polytetrafluoroethylene (PTFE), expanded PTFE, polyethylene, urethane, or polypropylene.

EXAMPLES

Example 1: Magnesium rod with layer structure

- [0095] In this example, laser sintering is performed on the EOSINT M 270 (available
25 from EOS GmbH Electro Optical Systems, Munich, Germany) is used. The Nitrogen purge is replaced by Argon in order to prevent a reaction of the molten magnesium with the nitrogen.

- [0096] Starting with a flat magnesium rod (99.9% purity, Sigma Aldrich, Cat. #299405), a vertical solid rod is made (length 15 mm, diameter 2 mm) by injecting magnesium powder

(magnesium, ReagentPlus™, ≥99% purity, powder, particle size –50 mesh, Sigma Aldrich Cat. #253987). The finished rod is cut from the original rod.

[0097] In a second step, the outer surface of the as-made magnesium rod is nitrided by exposing the surface to a 248 nm laser operating at 30 ns pulses (Iamba Physic SX 200K),
5 and by focusing the beam to a rectangular area of 1 mm by 16 mm long along the central axis of the rod. This results in an energy fluence of 4J/cm². Ten pulses are given at each position after which the tube is rotated 60 degrees. Nitrogen gas is flushed over the tube during the laser treating. The process is carried out at room temperature and at atmospheric pressure.

[0098] In a third step, an additional layer of magnesium is added to the outer surface of
10 the magnesium rod by mounting the rod sideways in the EOSINT M 270, which allows deposit of a 20 micrometer thick layer of magnesium by spiraling the rod underneath the laser beam / powder feeder.

[0099] This cycle of nitriding and adding a 20 micrometer thick layer is repeated 6 times. The as made rod consists of a core of magnesium and 7 layers of pure magnesium and
15 intermediate layers of Mg₂N₃ alloy. This rod is removed from the laser processing station and a central hole (diameter 2 mm) is drilled along the central axis of the rod. A stent pattern is made out of this tube by cutting a pattern using a femtosecond laser.

[0100] All non-patent literature publications, patent applications, patent application
20 publications, and patents, referred to in the instant application are incorporated herein by reference in their entirety.

[0101] Other embodiments are to be found within the appended claims.

WHAT IS CLAIMED IS:

1. A method of making a support structure for a medical device, the method comprising:
constructing, on the support structure, a first layer of a first material by direct metal laser sintering; and
introducing a first nitrogen content into a first part of the first layer by excimer laser nitriding.
2. The method of claim 1, wherein the medical device is an endoprosthesis.
3. The method of claim 2, wherein the endoprosthesis is a stent.
4. The method of claim 1, further comprising:
constructing a second layer of a second material, upon the first layer, by direct metal laser sintering.
5. The method of claim 4, further comprising:
introducing a second nitrogen content into a second part of the second layer by excimer laser nitriding.
6. The method of claim 4, further comprising:
constructing a third layer of a third material, upon the second layer, by direct metal laser sintering.
7. The method of claim 6, further comprising:
introducing a third nitrogen content into a third part of the third layer by excimer laser nitriding.
8. The method of claim 6, further comprising:

constructing further alternating layers on the third layer, wherein the alternating layers comprise, in sequence, a direct metal laser sintered layer, and a direct metal laser sintered layer having a nitrogen content introduced by excimer nitriding.

9. The method of claim 1 wherein the first material is a metal selected from the group consisting of: alkali metals, alkaline earth metals, iron, zinc, and aluminum.
10. The method of claim 9 wherein the metal is magnesium
11. The method of claim 4 wherein the metal is iron.
12. The method of claim 1, wherein the first material comprises a metal alloy.
13. The method of claim 1, wherein the first material is a biodegradable metal.
14. The method of claim 1 wherein the support structure has a shape, and wherein the shape is generally tubular.
15. The method of claim 1 wherein the first part of the first layer is the entirety of the first layer.
16. The method of claim 1 wherein the first material comprises platinum nanoparticles.
17. The method of claim 11 wherein the second material is magnesium.
18. The method of claim 17 wherein, after excimer nitriding, the second layer has a ratio of nitrogen to magnesium of less than 0.45.
19. The method of claim 17 wherein, after excimer nitriding, the second layer has a ratio of nitrogen to magnesium of greater than 0.45.

20. The method of claim 1 wherein the direct metal laser sintering is laser-engineered net shaping.
21. A medical device for implantation into an organism, the device comprising:
a support structure made by a process of claim 1.
22. The medical device of claim 21 wherein the support structure is biodegradable.
23. A method of using a medical device according to claim 21, comprising:
implanting the medical device in a body passageway of an organism.
24. A method of controlling corrosion of a medical device in an organism,
comprising:
constructing a support structure by building up alternating layers by direct metal laser sintering, and by excimer nitriding; and
implanting the device into the organism,
wherein the corrosion of the support structure occurs over a first period of time inside the organism.
25. The method of claim 24 wherein the implanting is carried out by:
disposing the device on a catheter;
inserting the catheter, with the device thereon, into the body passageway;
placing the device at a predetermined position in the body passageway; and
removing the catheter.
26. The method of claim 24 wherein the device is compacted prior to the disposing, and wherein the placing further comprises expanding the device at the predetermined position.
27. The method of claim 24, wherein the device is an endoprosthesis.

28. The medical device of claim 24 wherein the first period of time is between about 60 days and about 1,000 days.
29. The method of claim 24 wherein the first period of time is between about 120 days and about 750 days.
30. The method of claim 24 wherein the first period of time is between about 180 days and about 600 days.
31. The method of claim 24 wherein the corrosion comprises a mass reduction of at least about 50% of the structure.
32. A medical device comprising a support structure, wherein the support structure comprises alternating layers, and wherein the alternating layers comprise a first layer of fully-dense metal, and a second layer adjacent to the first layer, the second layer having a nitrogen content introduced by excimer laser nitriding.

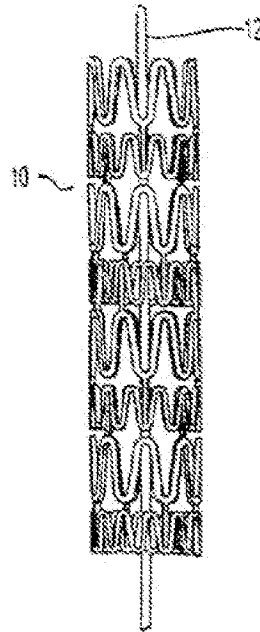


FIG. 1A

FIG. 1B

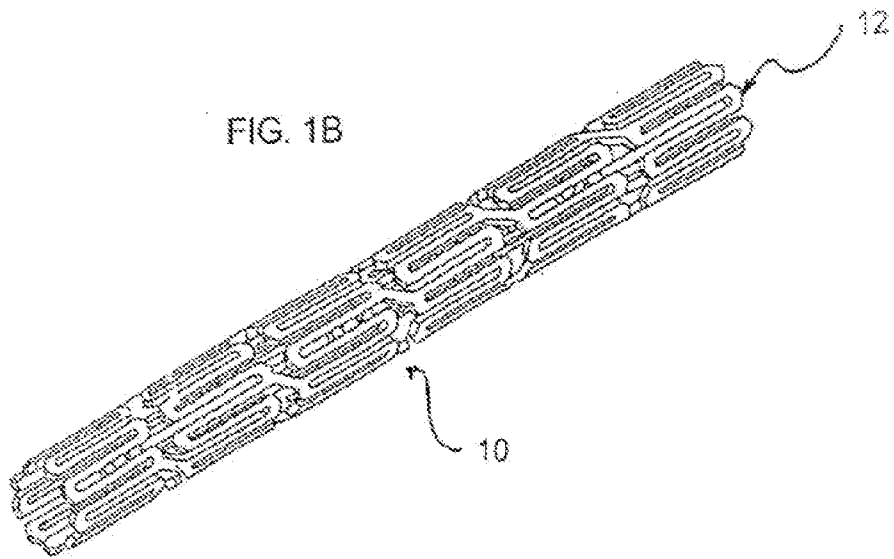
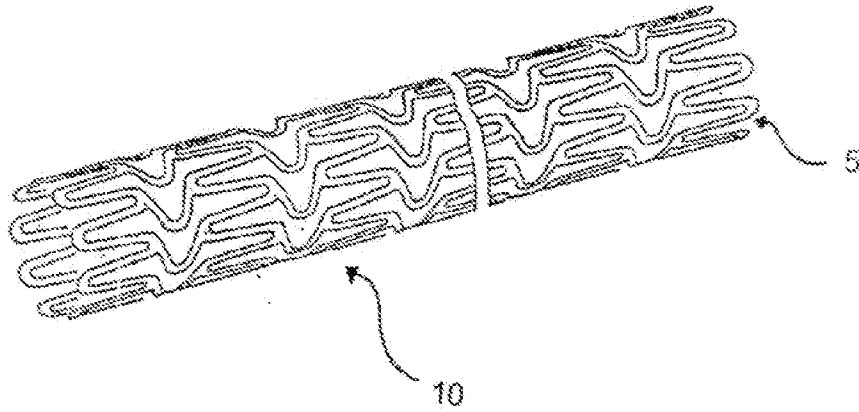


FIG. 1C



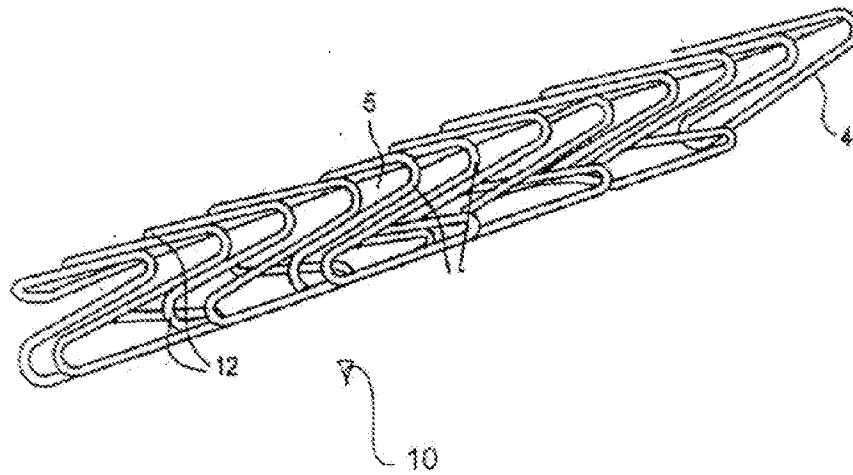
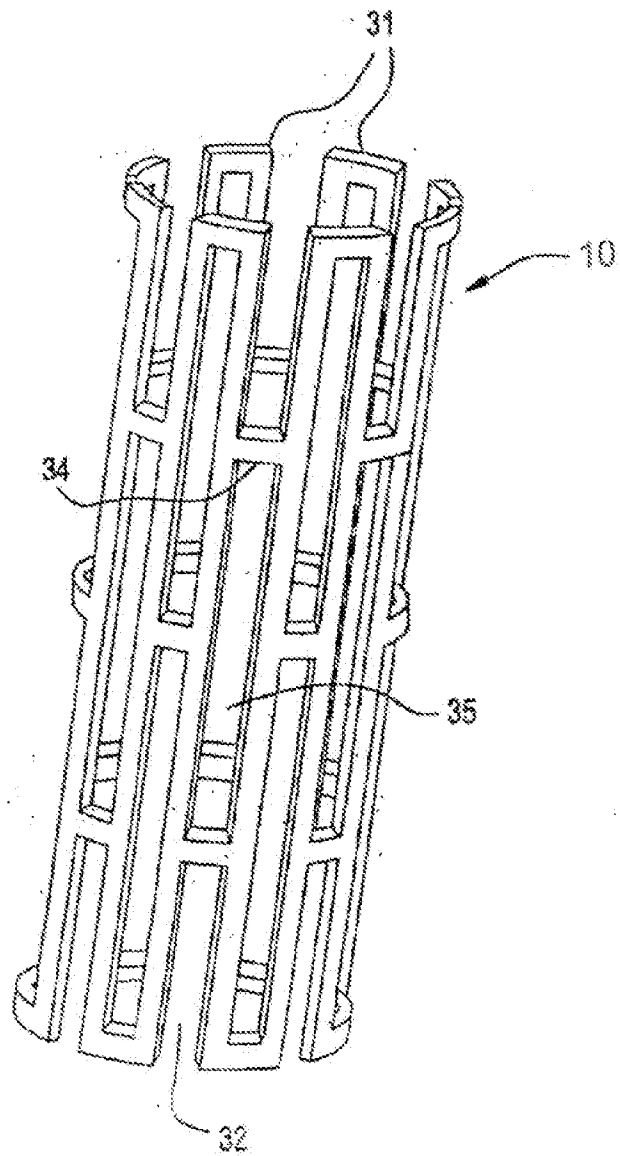


FIG. 1D

FIG. 1E



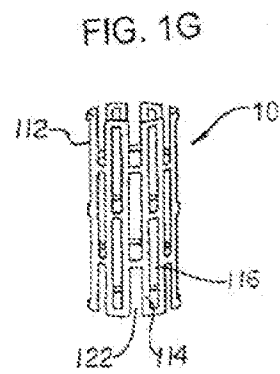
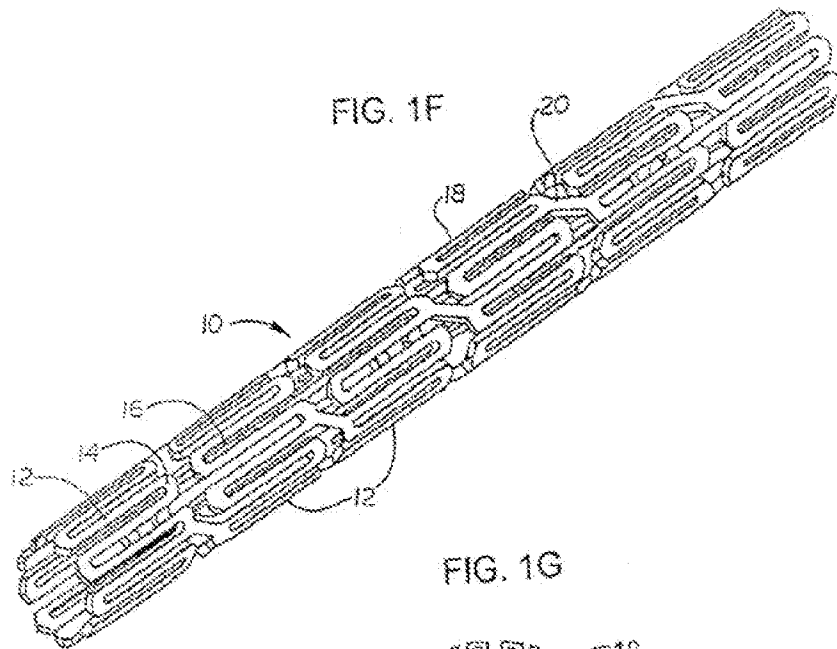
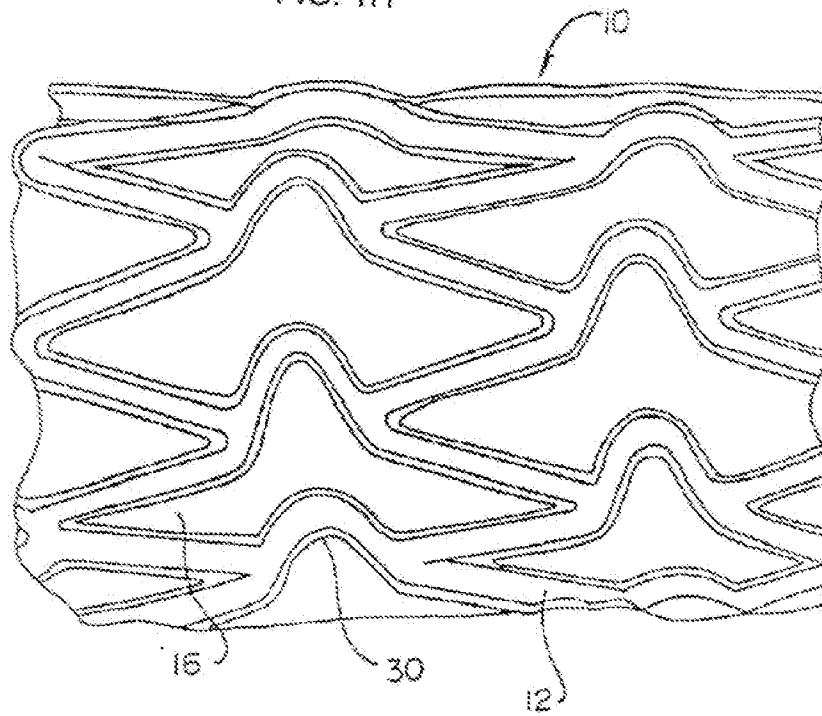
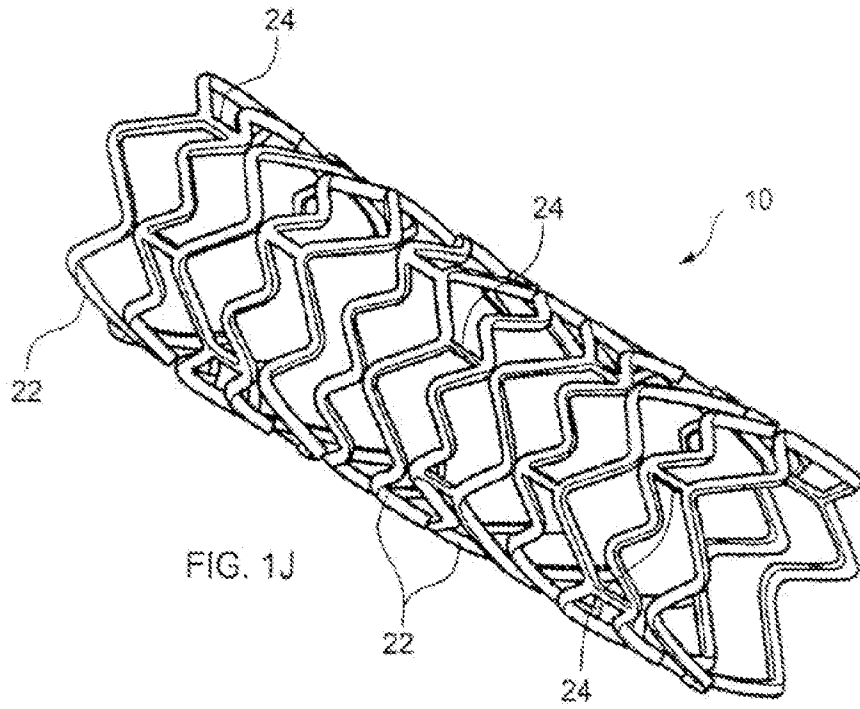


FIG. 1H





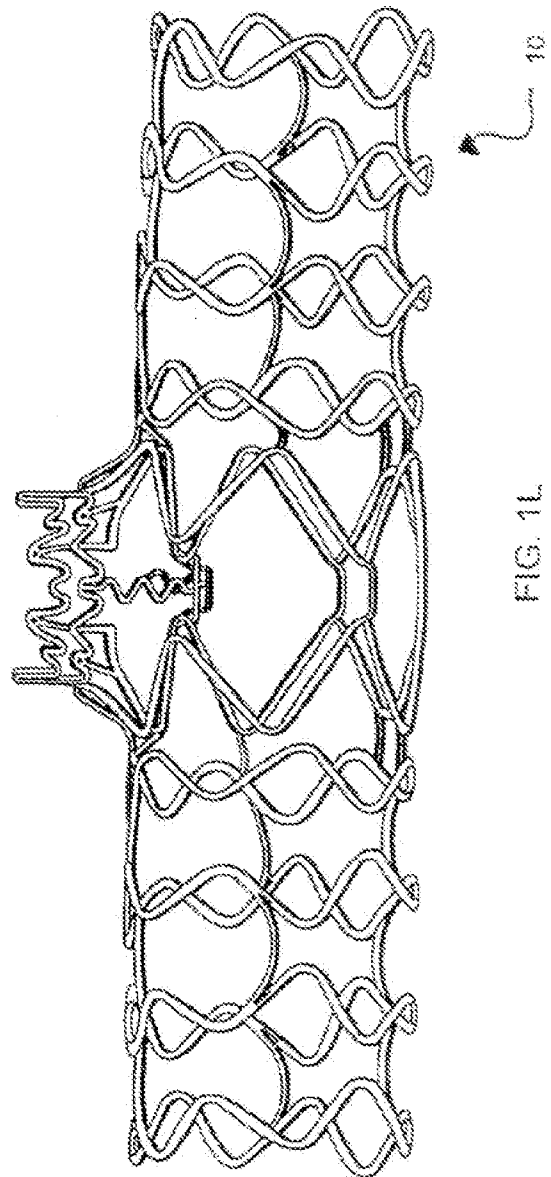
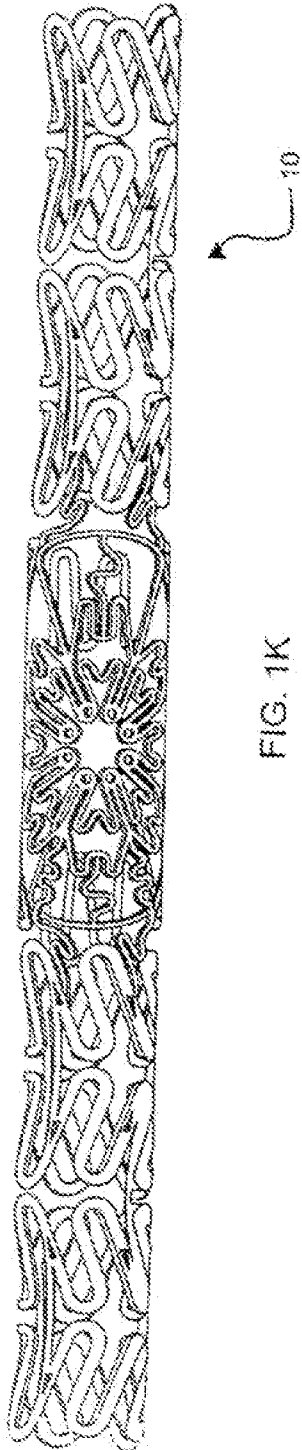


FIG. 2A

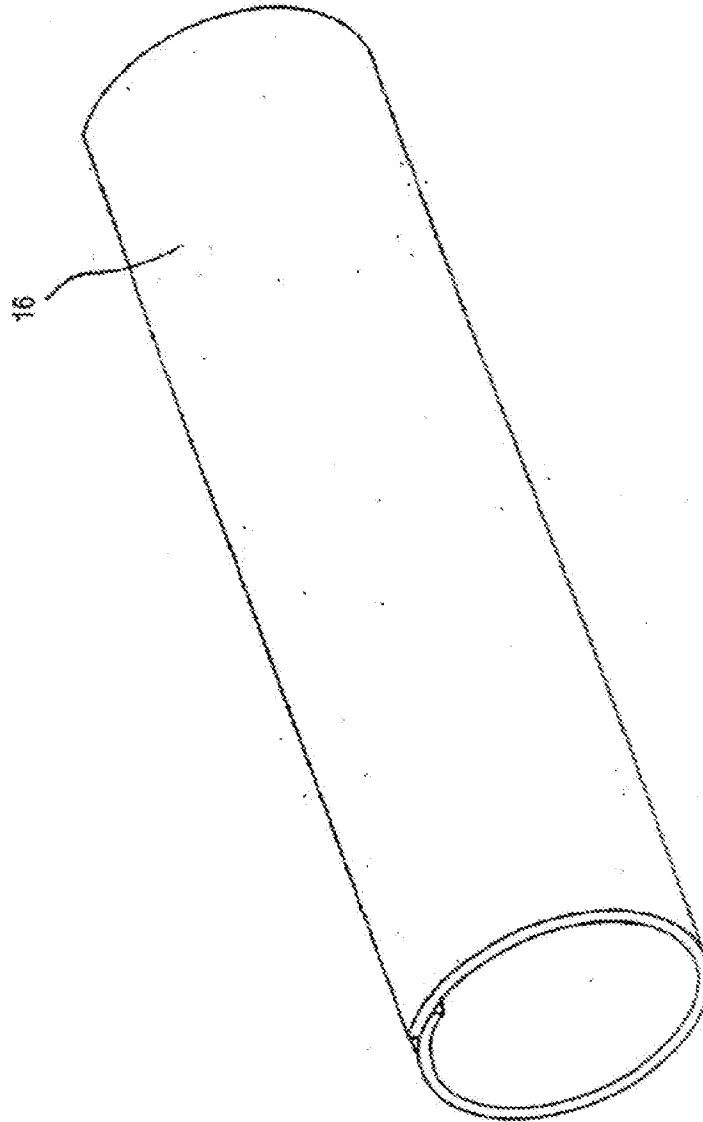


FIG. 2B

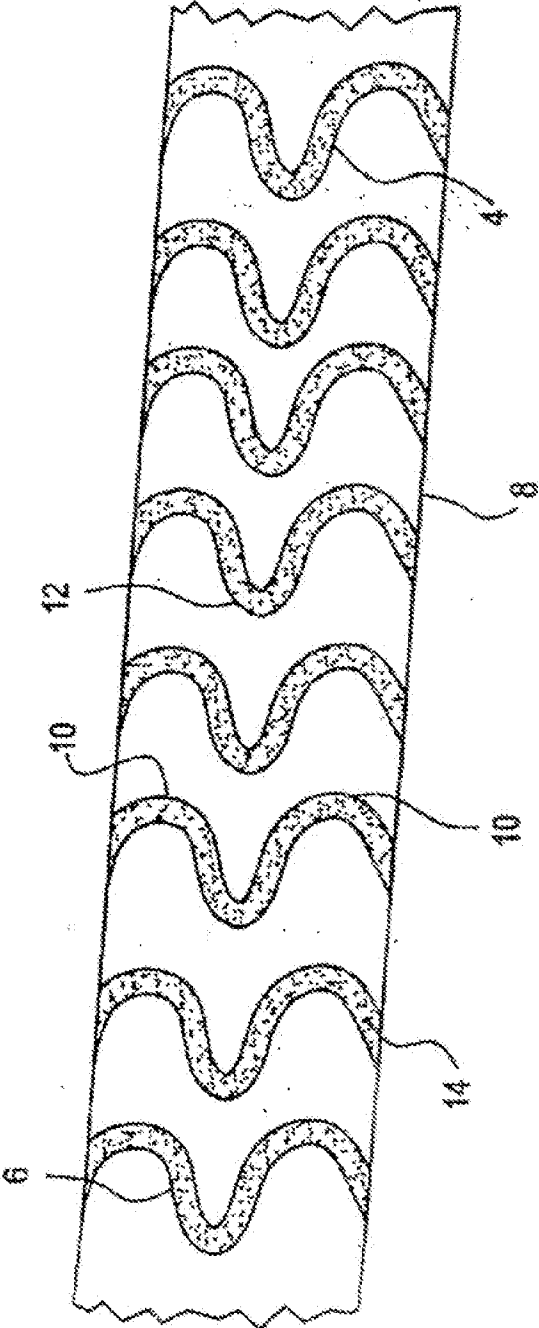
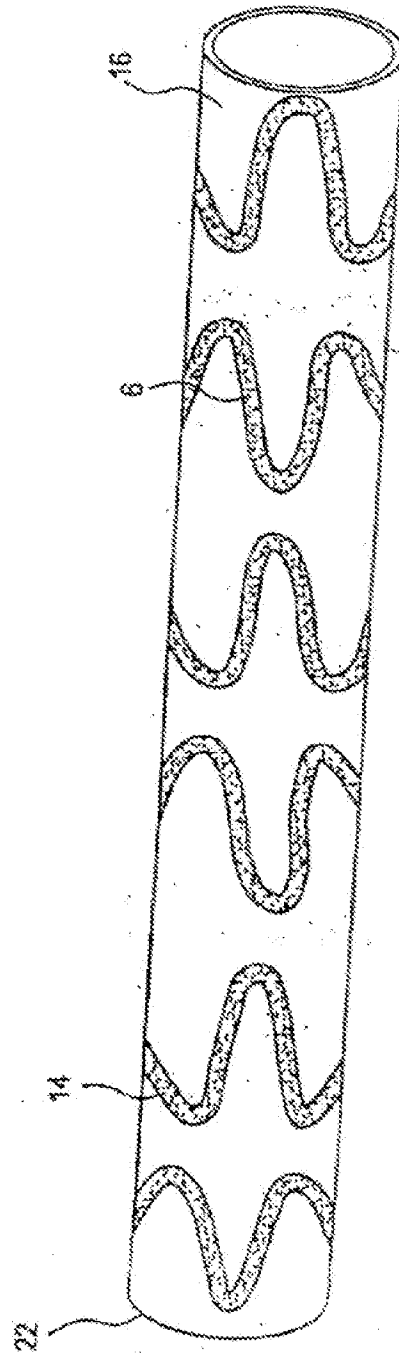


FIG. 2C



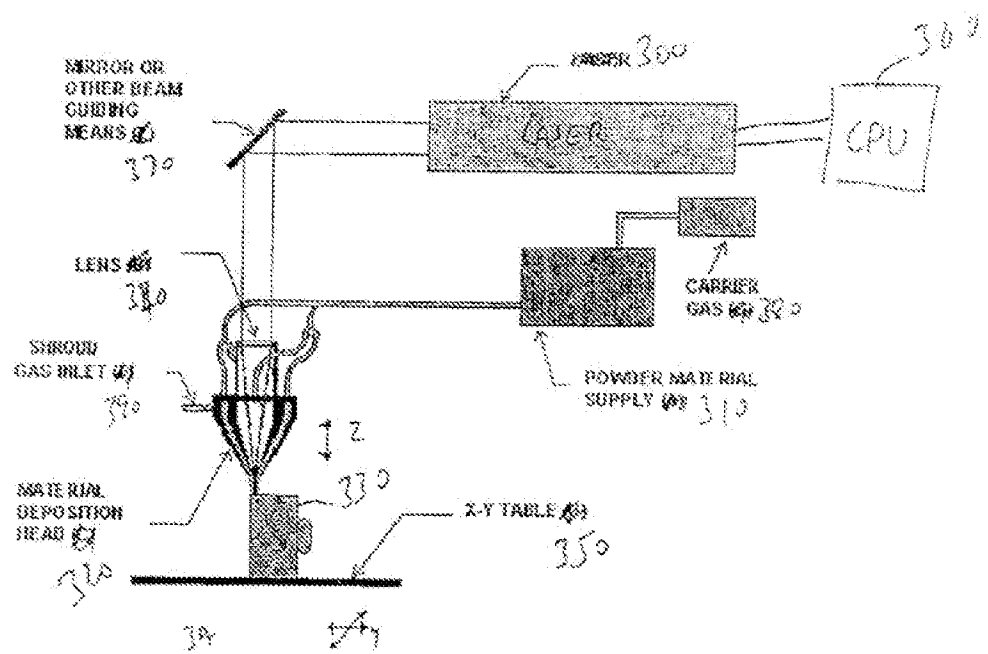


Fig. 8. Laser engineered net shaping.

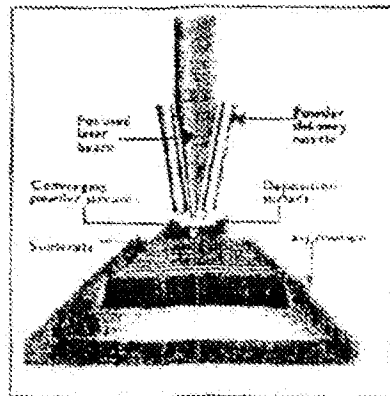


Figure 1: The LENS system.

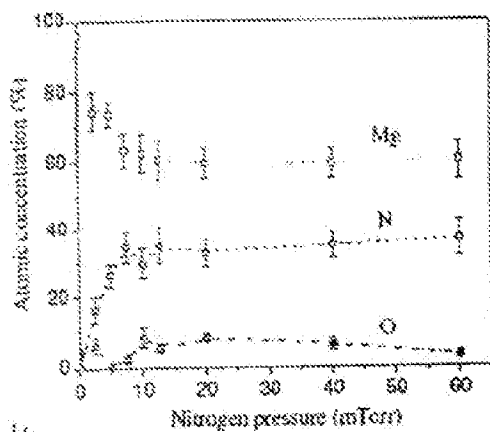
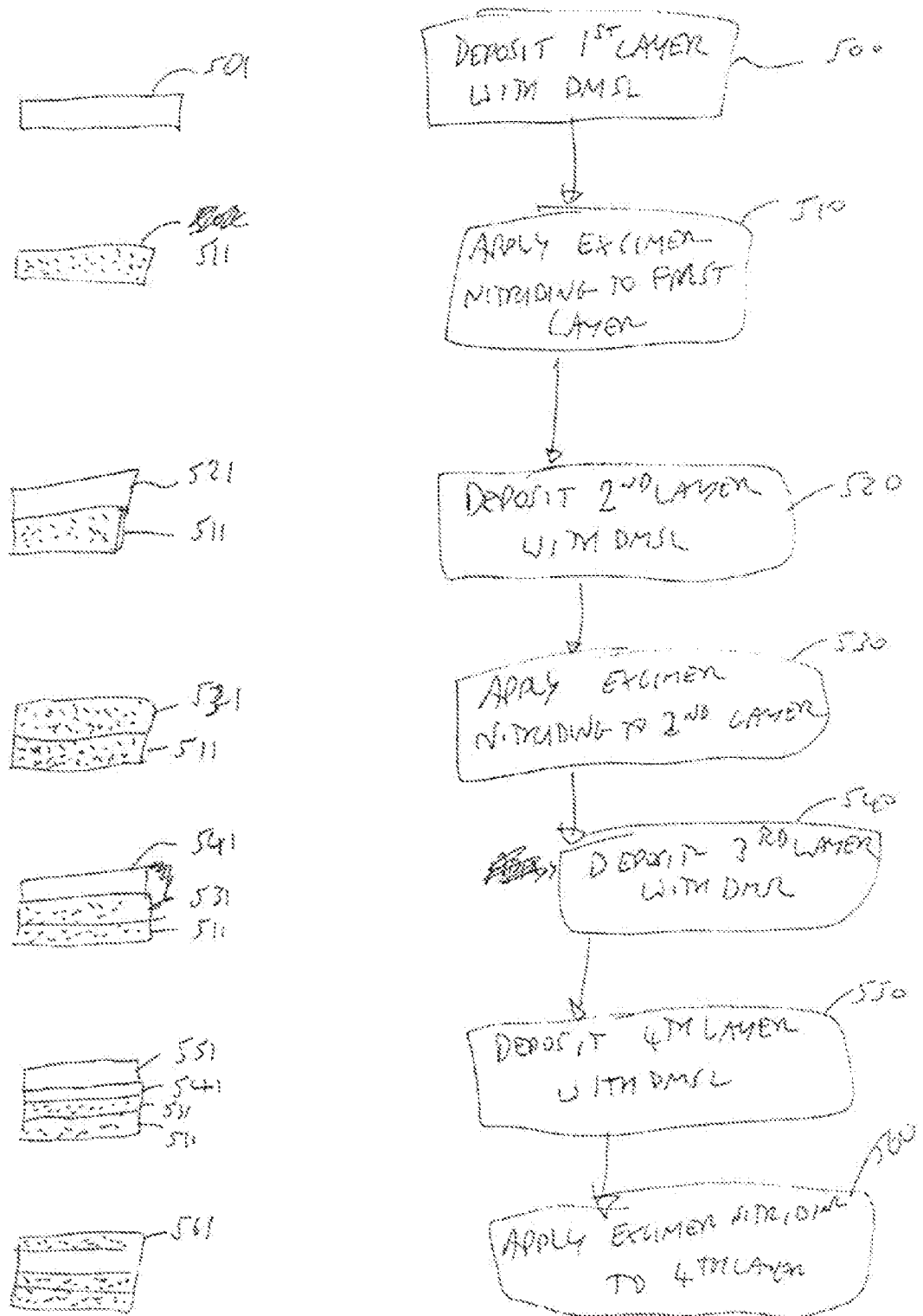
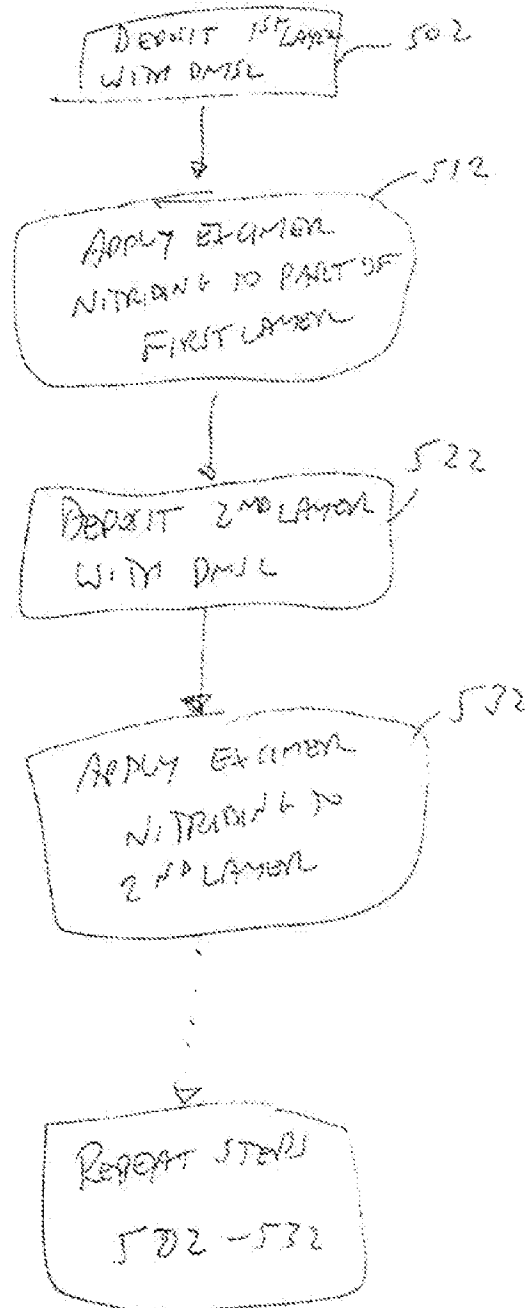
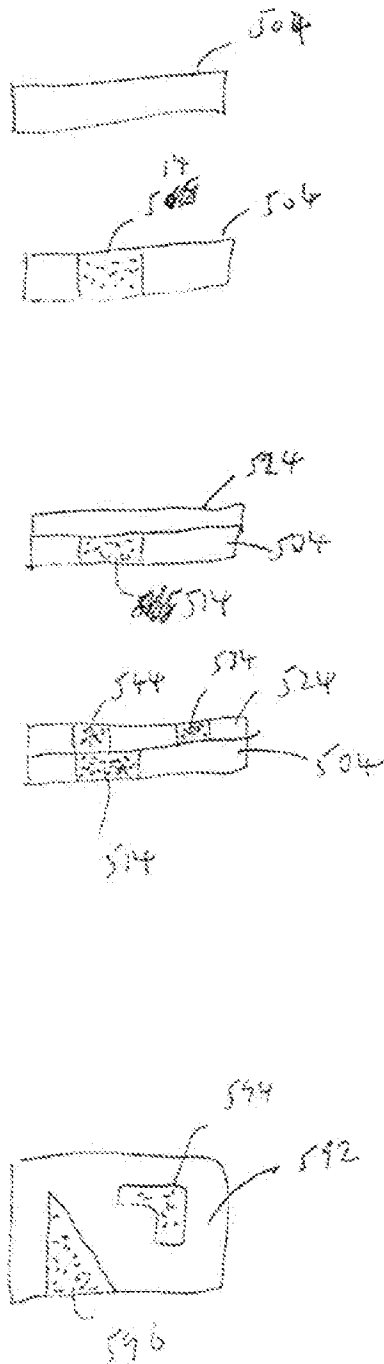


Fig. 3 Atomic concentration determined by XPS as a function of nitrogen gas pressure. The error bars on the concentration data are shown too.





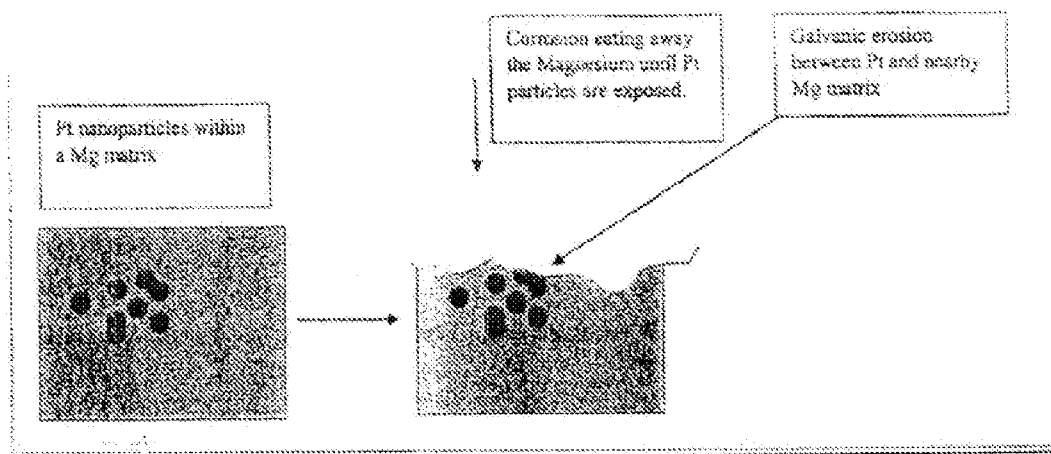


Fig. 6