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(54) **HARDENED POLYMERIC LUMEN SURFACES**

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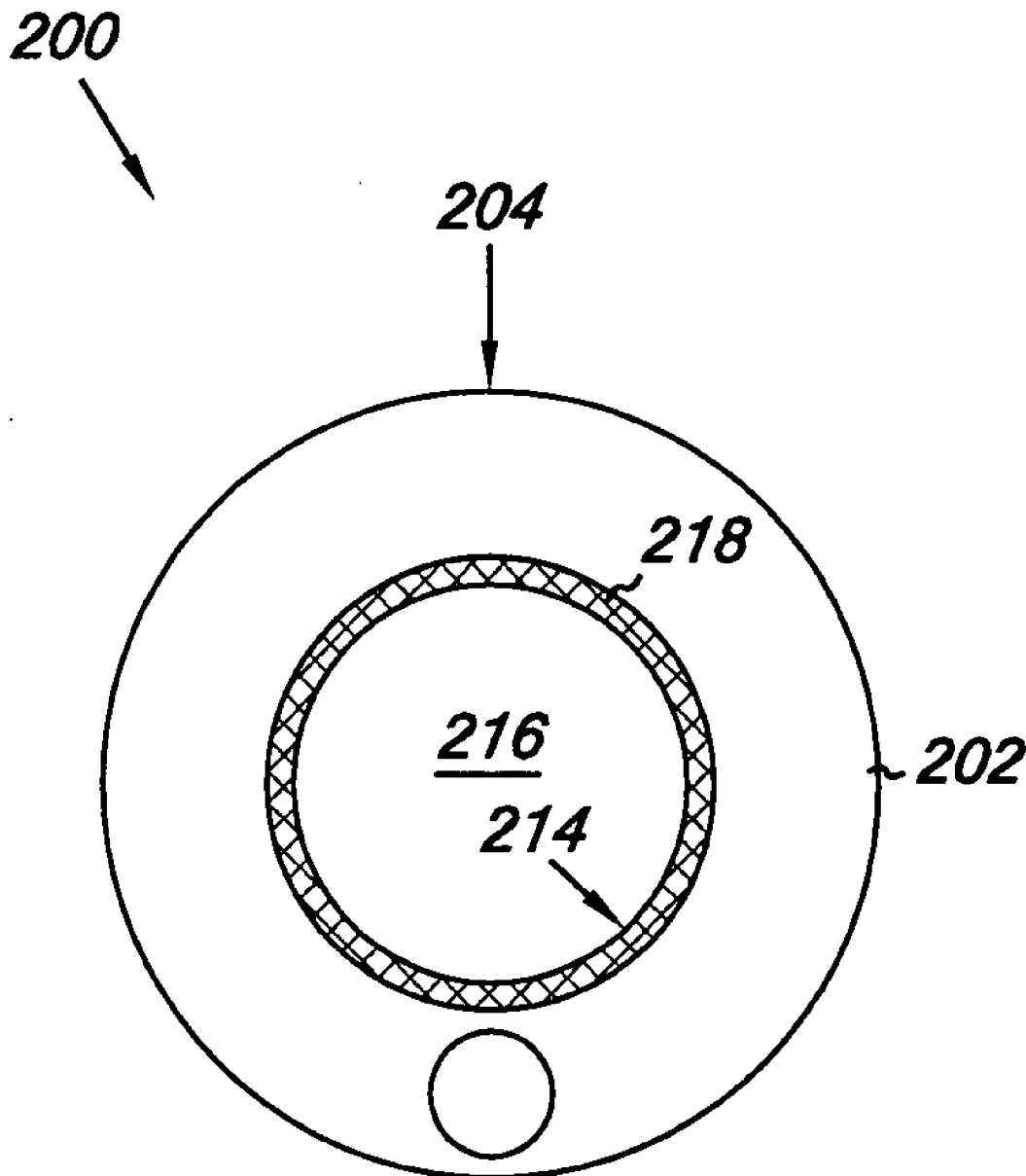
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(57) **ABSTRACT**

Apparatuses, systems, and methods for surface modification of catheters. The surface modification can be localized to a lumen surface of the catheter. The surface modification to the lumen surface extends radially into the catheter body a pre-determined distance to provide a hardened zone having a hardness that is greater than a hardness of an exterior surface of the catheter body.

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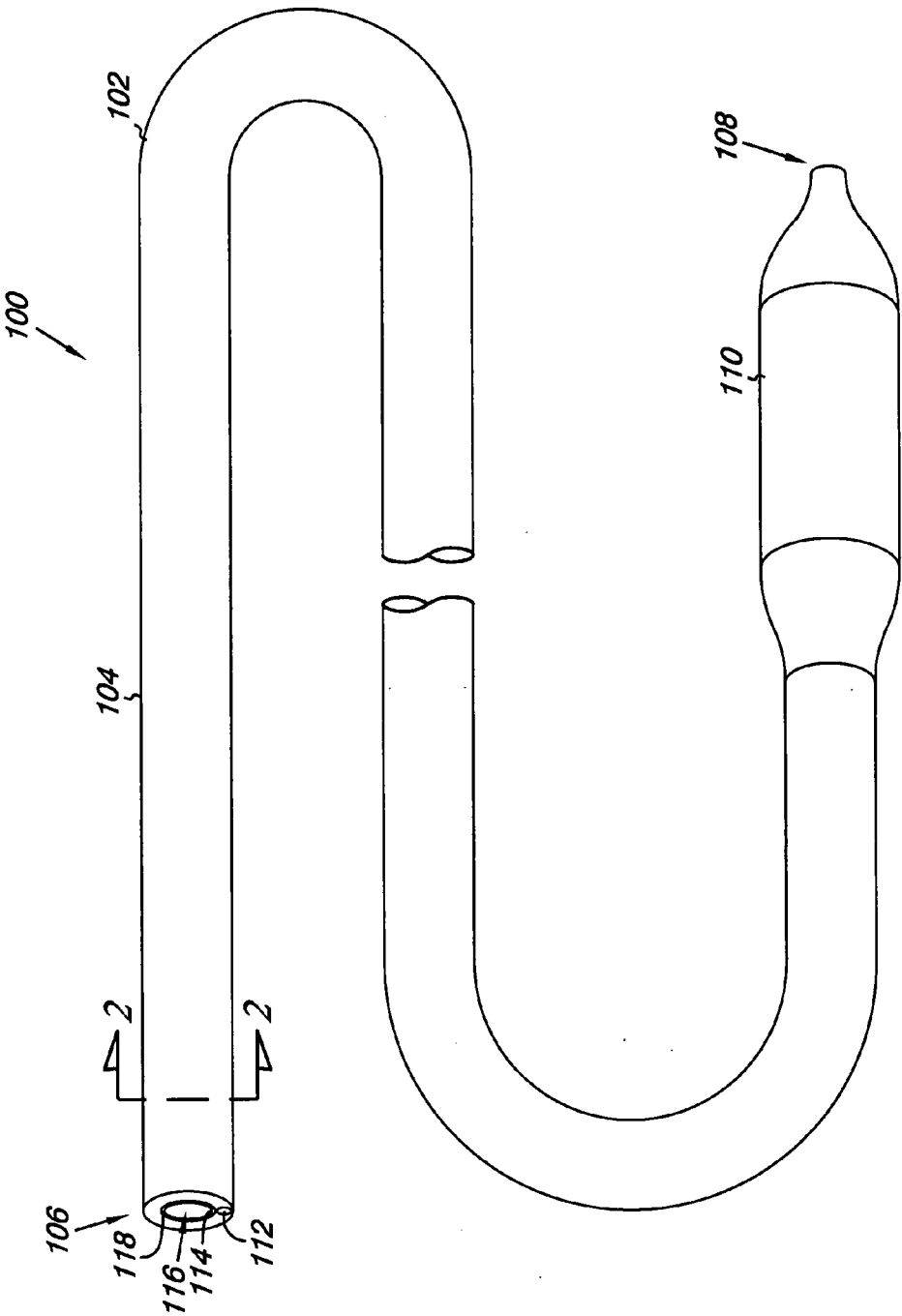


Fig. 1

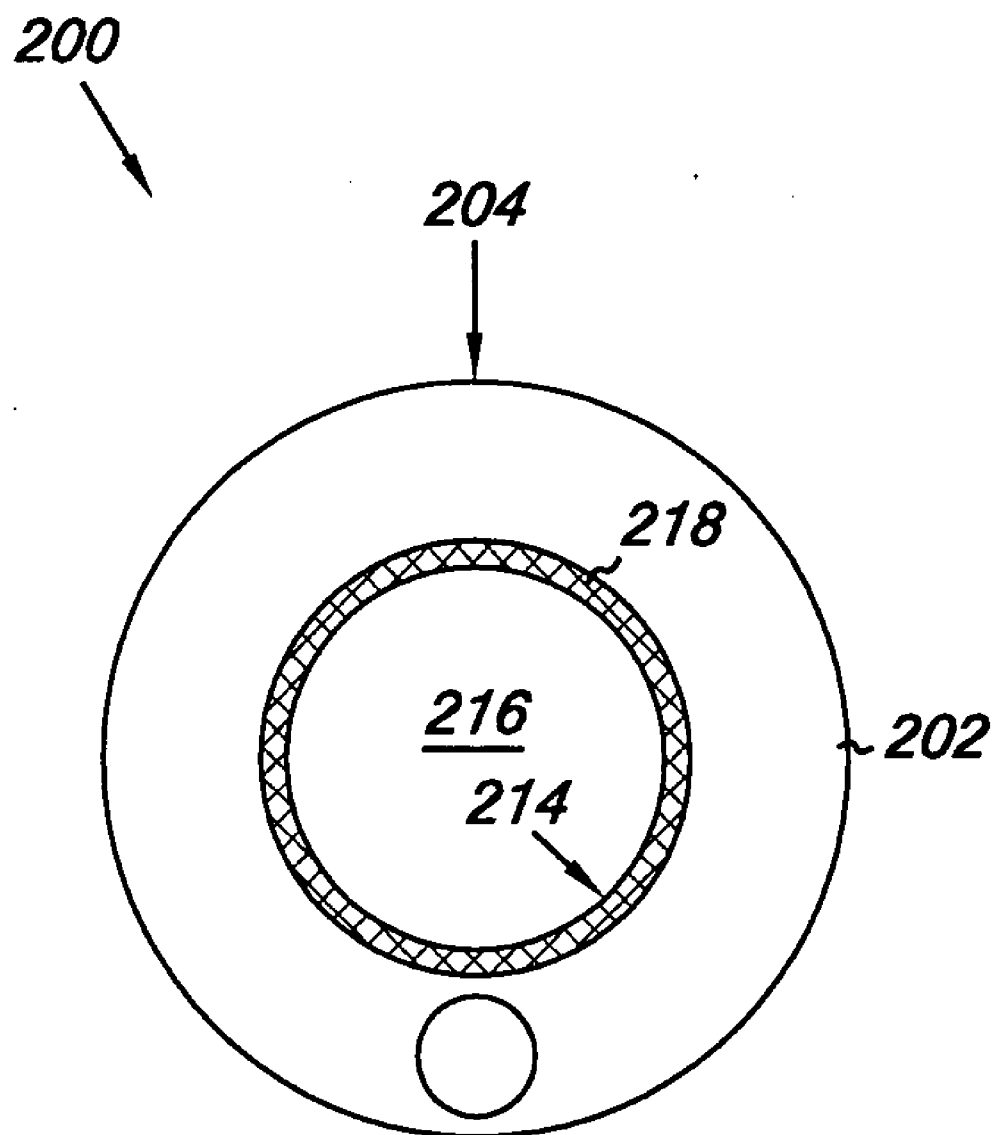


Fig. 2

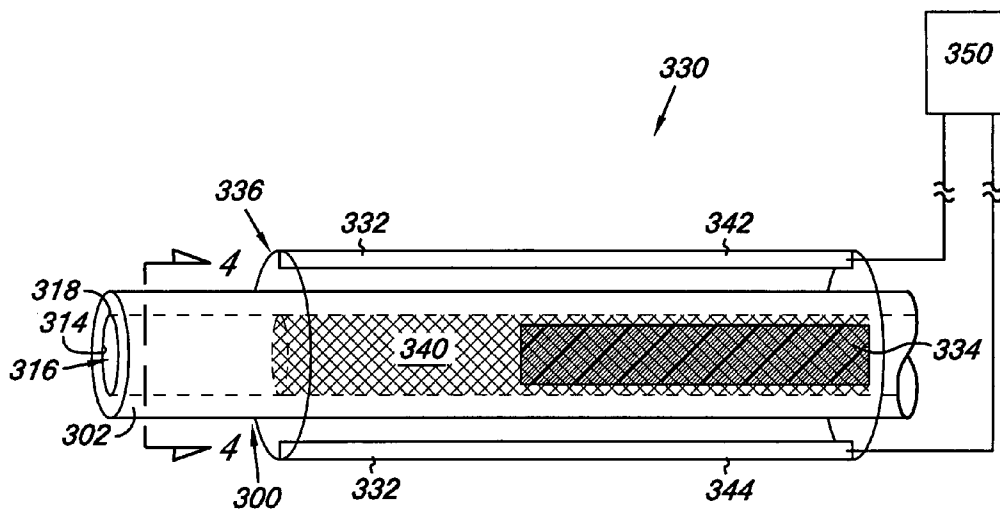


Fig. 3

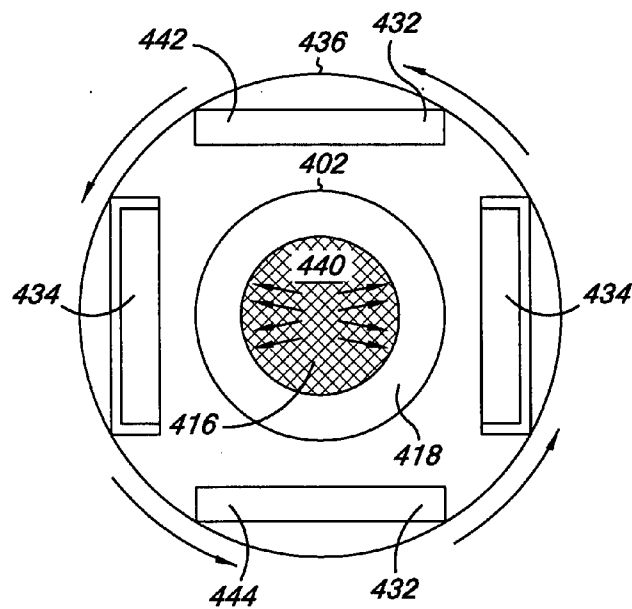


Fig. 4

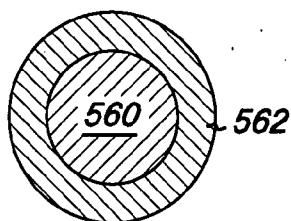


Fig. 5A

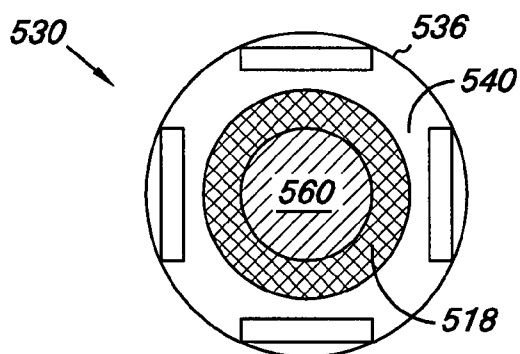


Fig. 5B

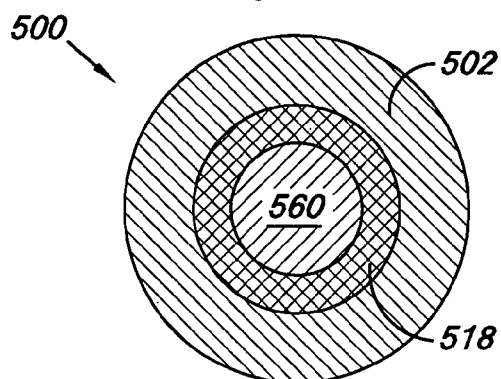


Fig. 5C

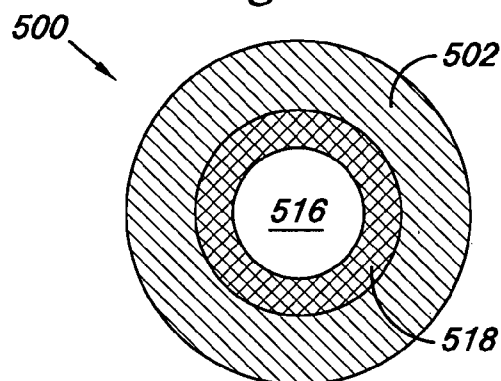


Fig. 5D

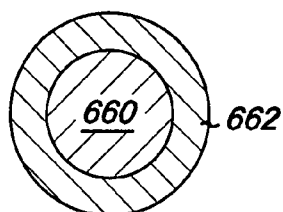


Fig. 6A

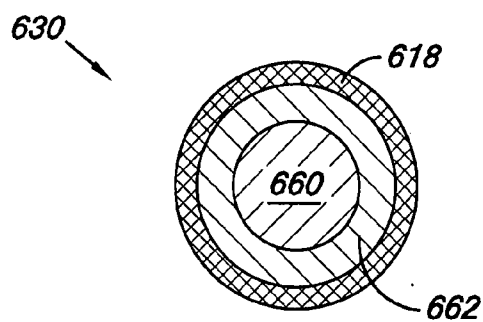


Fig. 6B

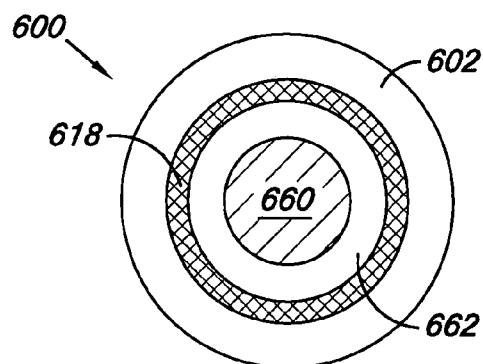


Fig. 6C

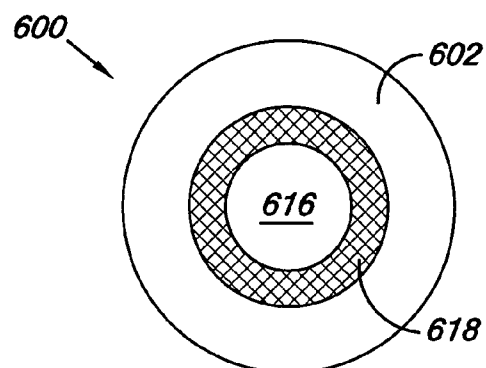


Fig. 6D

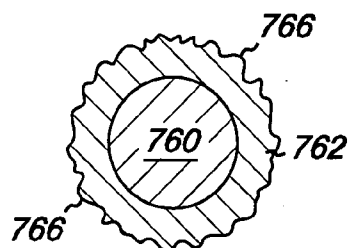


Fig. 7A

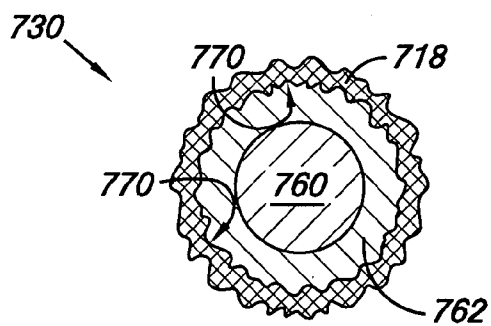


Fig. 7B

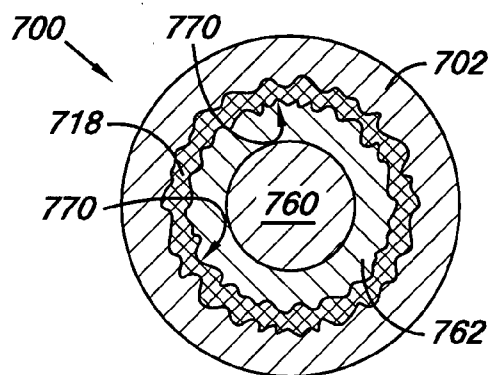


Fig. 7C

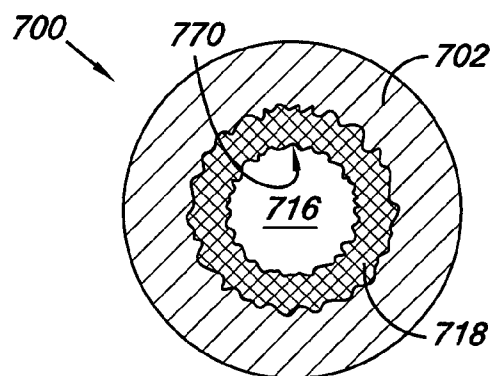


Fig. 7D

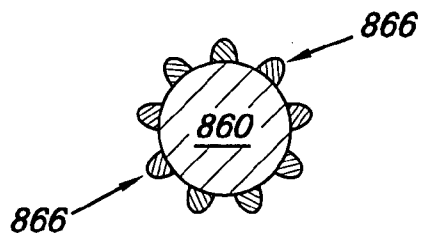


Fig. 8A

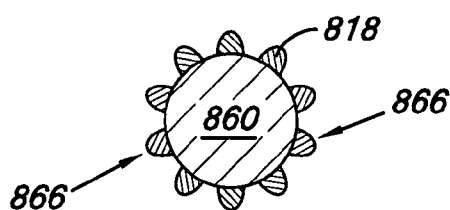


Fig. 8B

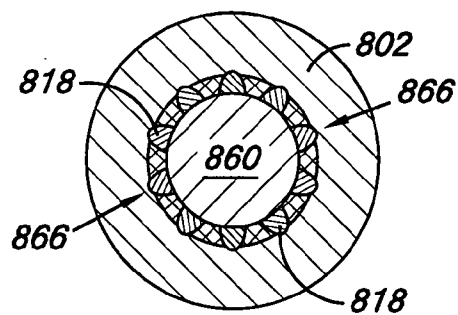


Fig. 8C

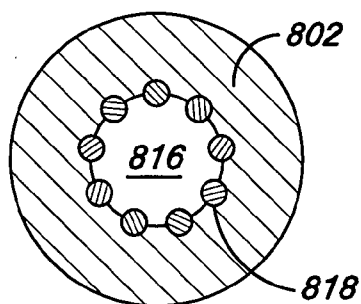


Fig. 8D

HARDENED POLYMERIC LUMEN SURFACES

TECHNICAL FIELD

[0001] The present disclosure relates generally to catheters, and more particularly to catheters having modified surfaces.

BACKGROUND

[0002] Friction encountered between wires and catheter lumen surfaces or between catheters and the inside of the lumen of guiding catheters provides a significant hurdle in the ability to smoothly steer and rotate the wires and/or catheters inside of the human body. A suitable approach to address this problem is needed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] FIG. 1 illustrates an embodiment of a catheter having a lumen surface with a hardened zone according to the present disclosure.

[0004] FIG. 2 illustrates a cross sectional view of the catheter of FIG. 1 taken along lines 2-2 according to one embodiment of the present disclosure.

[0005] FIG. 3 illustrates an apparatus for the surface modification of a lumen surface of a catheter according to one embodiment of the present disclosure.

[0006] FIG. 4 illustrates a cross sectional view of the apparatus and the catheter of FIG. 3 taken along lines 4-4 according to the present disclosure.

[0007] FIGS. 5A-5D illustrate the formation of a catheter having a hardened zone according to one embodiment of the present disclosure.

[0008] FIGS. 6A-6D illustrate the formation of a catheter having a hardened zone according to one embodiment of the present disclosure.

[0009] FIGS. 7A-7D illustrate the formation of a catheter having a hardened zone according to one embodiment of the present disclosure.

[0010] FIGS. 8A-8D illustrate the formation of a catheter having a hardened zone according to one embodiment of the present disclosure.

DETAILED DESCRIPTION

[0011] Embodiments of the present disclosure are directed to apparatuses, systems, and methods for surface modification of catheters. For the various embodiments, the surface modification can be localized to a lumen surface of the catheter. The surface modification to the lumen surface extends radially into the catheter body a predetermined distance to provide a hardened zone.

[0012] As used herein, a “hardened zone” includes a region of the material forming at least a portion of the catheter that extends from the lumen surface toward an exterior surface of the catheter, where the material in the region of the hardened zone has undergone at least a partial modification from energy delivered by ions driven into the elongate body according to the methods of the present disclosure. For the various embodiments, the hardened zone can provide either a non-discrete or discrete layer resulting from a change to the material forming the catheter.

[0013] For the various embodiments, the catheter includes a polymeric elongate body that is subjected to at least a partial modification by an ion treatment discussed herein. The ion treatment of the present disclosure can result in the formation

of a high level of macromolecule defects in a thin surface layer of the catheter material to form the hardened zone. For the various embodiments, the macromolecule defects cause structure transformations of the polymer chains through chemical reactions of free radicals formed by the ions, which can cause the formation of the hardened zone.

[0014] As used herein, a “modification” of the polymer chains forming the polymeric elongate body includes disrupting and recombining carbon-carbon bonds of the polymeric material to form structures ranging from amorphous carbon, fully carbonized or graphitized, partially carbonized to diamond like structures.

[0015] In addition, the thickness of the hardened zone can correspond to the distribution of defects which are determined by the energy and the kind of ions and/or the kind of polymer used in forming the polymer elongate body. The depth of the modification can be from several tens of nanometers to hundreds of nanometers, as will be discussed herein.

[0016] As used herein, the terms “a,” “an,” “one or more,” and “at least one” are used interchangeably. In addition, it is recognized that the surface modification of the present disclosure is not limited to lumen surfaces and can be used on other areas and/or regions of a catheter in addition to the lumen surface.

[0017] Unless otherwise indicated, all numbers expressing quantities of ingredients, processing conditions, and so forth used in the disclosure and claims are to be understood as being modified in all instances by the term “about.” Accordingly, unless indicated to the contrary, the numerical parameters set forth in the following specification and attached claims are approximations that may vary depending upon the desired properties sought to be obtained by the present disclosure. At the very least, each numerical parameter should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques.

[0018] For the various embodiments, the hardened zone formed at and extending from the lumen surface results in a surface having a material hardness that is greater than the material hardness of other polymer regions of the catheter body. For the various embodiments, the hardened zone can be formed from the polymeric material that forms (i.e., constitutes) the unmodified catheter (i.e., the catheter before surface modification according to the present disclosure). In other words, the hardened zone is formed in the polymeric material forming the catheter body, as apposed to being applied to polymeric material of the catheter body.

[0019] For the various embodiments, the hardened zone of the present disclosure provides for reduced contact frictional forces between the lumen surface and an item being moved relative thereto (e.g., through the lumen) as compared to an unmodified catheter. Such items can include, but are not limited to guidewires, balloon catheters, enclosed self-expanding stents, surgical instruments guided through endoscopic catheters or urological catheters (such as kidney stone retrieval baskets), and/or additional catheters. In addition, the presence of the hardened zone does not significantly, if at all, affect the bulk physical properties of the catheter as compared to an unmodified catheter. In other words, a catheter having the hardened zone according to the present disclosure display essentially the same bulk mechanical properties (e.g., stiffness, elongation at breaking, modulus of elasticity, tensile strength, stress-strain response, flexibility, etc.) as an identical catheters not having the hardened zone of the present

disclosure. In addition, the hardened zone also resists sloughing or flaking of the polymeric material that forms the hardened zone.

[0020] The figures herein follow a numbering convention in which the first digit or digits correspond to the drawing figure number and the remaining digits identify an element or component in the drawing. Similar elements or components between different figures may be identified by the use of similar digits. For example, **110** may reference element “10” in FIG. 1, and a similar element may be referenced as **210** in FIG. 2. As will be appreciated, elements shown in the various embodiments herein can be added, exchanged, and/or eliminated so as to provide any number of additional embodiments of the present disclosure. In addition, as will be appreciated the proportion and the relative scale of the elements provided in the figures are intended to illustrate the embodiments of the present invention, and should not be taken in a limiting sense.

[0021] FIG. 1 provides an embodiment of a catheter **100** according to the present disclosure. The catheter **100** includes a polymer elongate catheter body **102** having an exterior surface **104** that extends from a first end **106** to a second end **108**. As illustrated, the catheter **100** further includes an inflatable balloon **110** positioned around the catheter **100**. An inflation lumen **112** extends from the first end **106** of the polymer elongate catheter body **102** to be in fluid communication with an interior chamber of the inflatable balloon **110** to allow the balloon **110** to be inflated and deflated.

[0022] The catheter **100** further includes a lumen surface **114** that defines a lumen **116**. In one embodiment, the lumen **116** extends from the first end **106** to the second end **108**. Alternatively, the lumen **116** can extend from the first end **106** to a location between the first and second ends **106** and **108**.

[0023] The catheter **100** further includes a hardened zone **118** according to the present disclosure. For the present embodiments, the hardened zone **118** originates from the polymer structure forming the polymer elongate catheter body **102** through the modification processes described herein. In one embodiment, the hardened zone **118** of the lumen surface **114** can be a continuous surface of the modified polymeric material. Alternatively, the hardened zone can have a discontinuous surface with a predefined pattern, as will be discussed more fully herein.

[0024] In one embodiment, the hardened zone **118** extends radially into the polymer elongate catheter body **102** from the lumen surface **114** to a predetermined depth. For the various embodiments, the predetermined depth of the hardened zone **118** can be from about 2 nanometers to about 400 nanometers. Alternatively, the thickness or depth of the hardened zone **118** can be from about 20 nanometers to about 200 nanometers, or from about 100 nanometers to about 200 nanometers. Alternatively, expressed as a percentage, the predetermined depth can have a value of 0.05 percent (%) through 10 percent (%) of the average wall thickness of the polymer elongate catheter body **102**.

[0025] For the various embodiments, the hardened zone **118** can have a material hardness value ranging from 1 Gpa (e.g., when formed from polymers having a high ratio of sp²/sp³ hybrid bonds) to 40 Gpa (e.g., when formed from polymers having mainly sp³ bonds). Measurements of the hardened zone **118** can be made using a Nano-Hardness Tester, for example from CSM Instruments Inc. (Needham, Mass., USA). The Nano-Hardness Tester is specially suited to load and penetration depth measurements at nanometer

length scales. The Nano-Hardness Tester(s) can also be used in the analysis of organic and inorganic soft and hard coatings.

[0026] For the various embodiments, the material hardness of the hardened zone can be uniform through its predetermined depth. Alternatively, the hardened zone **118** can have a material hardness value (e.g., 5.30 Gpa) that changes (e.g., decreases) in value from the lumen surface **114** through its predetermined depth. In addition, the thickness of the hardened zone **118** has little to no measurable effect on the bulk mechanical properties (e.g., stiffness, elongation at breaking, modulus of elasticity, tensile strength, stress-strain response, flexibility, etc.) of the polymer elongate catheter body **102**.

[0027] FIG. 2 provides a cross-sectional view of the catheter **100** taken along the lines 2-2 in FIG. 1. According to the embodiment illustrated in FIG. 2, the hardened zone **218** extends into the elongate body **202** from the lumen surface **214**. For the various embodiments, the hardened zone **218** can gradually transition from, for example, a carbonized region at the lumen surface **214** through a partially carbonized region of the polymeric material to a deeper unaffected polymeric material of the polymer elongate catheter body **202**.

[0028] In one embodiment, variation in the depth of the hardened zone **218** can be attributed to the surface modification process of the present disclosure in which ions are driven into the lumen surface **214** of the polymer elongate catheter body **202**. Depending on the energy of the ions being driven into the lumen surface **214**, the polymeric bonds of the polymer elongate catheter body **202** are disrupted and recombine as carbon-carbon structures, ranging from amorphous carbon to diamond like structures, up to a depth of several tens or hundreds of nanometers, as discussed herein. The resulting hardened zone **218** has a surface with a material hardness that is greater than both a hardness of the lumen surface before the surface modification and the exterior surface **204** of the polymer elongate catheter body **202**.

[0029] The carbonization and oxidation processes discussed herein can be observed in a variety of polymers. Suitable polymer include, block co-polymers of polyamide and polyether sold under the trade designator Pebax, nylons, polyurethanes, polyamides, polyethylene, silicone, latex, polyethylene terephthalate or other polyesters, polyvinylchloride, etc. More generally, polymers having a high content of carbon-carbon bonds are also suitable.

[0030] Referring back to FIG. 1, the lumen **116** is configured to receive and pass a guidewire for guiding and positioning the catheter **100** in the vasculature. In one embodiment, the hardened zone **118** allows for a reduced coefficient of friction (e.g., static and kinetic friction) between the lumen surface **114** and the guidewire as compared to an unmodified lumen surface of the same polymer elongate body under the same conditions (e.g., temperature, relative speed of the guidewire and catheter, the contact geometry the guidewire and catheter experience).

[0031] As will be appreciated, the hardened zone as discussed herein can be created in a number of different types of catheters. One example is the balloon catheter **100** illustrated in FIG. 1. Other examples include, but are not limited to, coronary guide catheters that can be used to pass guidewires and/or balloon catheters, including balloon catheters with a stent mounted thereto. An addition example includes a catheter or sheath used in holding, moving and/or delivering a self-expanding stent to an implant location in the body.

[0032] Other applications for the present disclosure can include surface modification of lumens in cardiac leads, such as pacing leads and/or defibrillation leads. In addition, surface modification according to the present disclosure can be used with a lumen surface of a medical device that has a small inner diameter (e.g., I.D. of 5 mm or less), which would benefit from a reduction in a coefficient of friction between the lumen of the medical device and one or more other structures that come in contact with the lumen.

[0033] FIG. 3 provides an illustration of an apparatus 330 for the surface modification of the catheter 300 as discussed herein. In one embodiment, the apparatus 330 can modify the catheter 300 by driving ions into the catheter 300. One example of driving ions into the catheter 300 can be through a Plasma Ion Immersion Implantation (PIII), in which high energetic ions (5-40 keV) are driven into the polymer surface of the catheter 300. As discussed herein, this surface modification produces the hardened zone 318 of the present disclosure in the catheter 300.

[0034] As illustrated, the apparatus 330 includes a first pair of plasma electrodes 332 and a second pair of implanting electrodes 334 positioned outside, around and adjacent to the exterior surface 304 of the polymer elongate body 302. The apparatus 330 further includes a housing 336 positioned around the plasma electrodes 332 and the implanting electrodes 334. In one embodiment, the housing 336 is formed of an electrically insulating material to better direct energy from the electrodes 332 and 334 across the elongate body 302 of the catheter 300. Examples of such materials include, but are not limited to, glass and polytetrafluoroethylene (PTFE). Other electrically insulating materials are known and could be used for the housing 336.

[0035] For the various embodiments, the plasma generating electrodes 332 can be used to create a plasma 340 of ions inside the lumen 316 of the catheter 300. In one embodiment, the plasma electrodes 332 can include a cathode 342 and an anode 344 positioned in an opposing configuration across the catheter 300. For the various embodiments, the catheter 300 can be feed through the apparatus 330 past the electrodes 332, where the electrodes 332 and the housing 336 are in close proximity to the exterior surface 304 of the elongate body 302 so as to prevent the formation of plasma outside the lumen 316.

[0036] For the various embodiments, the plasma electrodes 332 can be used to provide RF energy to a plasma gas being streamed through the lumen 316 to generate the plasma 340 inside of the lumen 316. In one embodiment, the plasma gas can include one or more of nitrogen (N_2), argon (Ar), xenon (Xe), helium (He), oxygen (O_2) and/or combinations thereof. For the various embodiments, the plasma gas can be streamed through the lumen 316 at a pressure in the range of 10^{-3} Pa through 10^{-1} Pa.

[0037] To generate the plasma 340, the plasma electrodes 332 can be operatively connected to a radiofrequency generator 350. For the various embodiments, the radiofrequency generator 350 can provide power at a desired frequency to the electrodes 332 to generate the plasma 340. For the various embodiments, the radiofrequency generator 350 can apply RF energy pulses at a predetermined frequency (i.e., a pulse repetition frequency) of 0.2 Hz to 200 Hz. In one embodiment, pulsing the RF energy helps to prevent overheating of the polymer elongate body 302 of the catheter 300 during the surface modification techniques in producing the hardened zone. In addition, the radiofrequency generator 350 can

deliver RF energy through the electrodes 332 at peak voltages in the range of 5 to 40 keV. Specific examples of such peak voltages include, but are not limited to, 5, 10, 20 and 30 keV.

[0038] The ions from the plasma 340 can then be driven into the lumen surface 314 using the second pair of implanting electrodes 334. For example, the second pair of implanting electrodes 334 can be used to accelerate and drive the ions from the plasma 340 into the wall of the lumen surface 314 to form the hardened zone 318 described herein.

[0039] In one embodiment, the implanting electrodes 334 can be used to deliver alternating negative and positive voltage pulses at a voltage of 20 to 40 keV across the implanting electrodes 334 at the predetermined frequency to accelerate and drive the ions from the plasma 340 into the wall of the lumen surface 314. For the various embodiments, the predetermined frequency can have a value of 100 to 600 Hz. For the various embodiments, this allows for doses of ions delivered from the plasma 340 to the lumen surface 314 to be from 5×10^{14} through 10^{17} ions/cm², where doses of 10^{16} ions/cm² or higher are also suitable.

[0040] The operating parameters of the apparatus 330 discussed herein can be used to form different configurations of the hardened zone 318 in the polymer elongate body 302. For example, the operating parameters can be used to create the hardened zone 318 that gradually transitions from one or more of an amorphous carbon, fully carbonized or graphitized, partially carbonized to diamond like surface to a non-hardened zone in the polymer elongate catheter body 302. In addition, the operating parameters can be used to control the depth, or thickness, of the hardened zone 318, as discussed herein, to maintain bulk mechanical properties of the polymer elongate catheter body 302.

[0041] For the various embodiments, the relative size and position of the plasma electrodes 332 and the implanting electrodes 334 can be configured to better maintain the stability of the plasma 340 inside the lumen 316 of the polymer elongate catheter body 302. In some situations the implanting electrodes 334 can disrupt the plasma 340 as they drive the ions into the elongate body 302. In one embodiment, the plasma electrodes 332 can extend past the implanting electrodes 334 upstream relative the direction of plasma gas flow to better maintain and supply the plasma 340 to the region of the implanting electrodes 334. For the various embodiments, the plasma electrodes 332 can be at least twice as long as the implanting electrodes 334 as measured in the direction of the longitudinal axis of the elongate body 302.

[0042] In addition embodiment, the supply of the plasma 340 formed with the plasma electrodes 332 can also be dependent upon both the flow rate of the plasma gas and the pulse frequency of the RF energy used to form the plasma 340. For example, the flow rate of the plasma gas and the pulse frequency of RF energy delivered from the plasma electrodes 340 can be adjusted so as to ensure that enough plasma gas is supplied between pulses to allow for more plasma 340 to be formed. As a result, the faster the pulse frequency of the RF energy, the faster the flow rate of the plasma gas may need to be.

[0043] In an additional embodiment, to better ensure the surface modification treatment of the present disclosure treats the entire lumen surface 314 of the elongate body 302, one or both of the electrodes 332 and 334 and/or the catheter 300 can be rotated relative each other around the longitudinal axis of the catheter 300. Also, to treat longer sections of catheters

300, the elongate body **302** can be feed past the electrodes **332** and **334** via a reel-to-reel system.

[0044] FIG. 4 provides a cross-sectional view of the apparatus **330** taken along the lines 4-4 in FIG. 3. As illustrated, the electrodes **432** and **434** and the housing **436** can rotate relative the elongate body **402** of the catheter **400**, or visa versa, to better ensure the ions being driven by the implanting electrode **434** are exposure around the lumen surface **414**. In an additional embodiment, both the apparatus **430** and the elongate body **402** can be rotated in opposite directions simultaneously.

[0045] FIGS. 5A-5D provide an additional embodiment of the catheter **500** according to the present disclosure. As discussed herein, the catheter **500** illustrates an embodiment in which the hardened zone **518** is formed as a discrete layer relative the remaining portions of the catheter **500**. In one embodiment, the hardened layer **518** can be formed having a uniform hardness value through the thickness of the hardened layer **518**.

[0046] For the various embodiments, a layer **562** of a first polymer material can be deposited on a mandrel **560**, as illustrated in FIG. 5A. For the various embodiments, the mandrel **560** can be an electrically conductive, flexible, ductile, metal or a metal alloy. Examples of suitable materials for the mandrel **560** include, but are not limited to, copper, brass, zinc, and PTFE coated soft metallic alloys.

[0047] In one embodiment, the first polymer material can be one or more of the polymers discussed herein. As will be appreciated, depositing the first polymer material on the mandrel **560** can be accomplished by a number of different coating techniques. Such techniques include, but are not limited to, spray coating, ultrasonic mist coating, dip coating, electrostatic coating, over-extrusion techniques and/or printing or patterning the polymer layer **562** on the mandrel **560**. Other coating techniques are also possible.

[0048] In one embodiment, the resulting polymer layer **562** can have a thickness of about 2 nanometers to about 400 nanometers, from about 20 nanometers to about 200 nanometers, or from about 100 nanometers to about 200 nanometers. Other thicknesses are also possible.

[0049] FIG. 5B provides an illustration of the mandrel **560** with its polymer layer **562** being fed through the apparatus **530** to form the hardened zone **518** in at least a portion of the first polymer material. As discussed herein, the apparatus **530** includes the housing **536**, the plasma electrodes **532** for generating the plasma **540** and the implanting electrodes **534** for driving the ions into the polymer layer **562**.

[0050] For the present embodiment, the mandrel **560** can be formed of an electrically conductive material to allow the mandrel **560** to be used as a pole (e.g., a cathode) in delivering alternating negative and positive voltage pulses, as discussed herein, for driving the ions into the polymer layer **562**. The result can be the formation of the hardened zone **518** from the polymer layer **562**. For the various embodiments, the entire polymer layer **562** can be formed into the hardened zone **518**, as discussed here. Alternatively, less than the entire polymer layer **562** can be formed into the hardened zone **518**, as will be more fully discussed herein.

[0051] For the various embodiments, the plasma gas, as discussed herein, used in forming the plasma **540** can be supplied between the electrodes **532**, **534** and the polymer layer **562**. For the various embodiments, the flow rate of the plasma gas can be dependent upon the frequency of the RF

pulses delivered from the plasma electrodes **532** and the desire to maintain a stable plasma **540**.

[0052] As discussed herein, the apparatus **530** and/or the mandrel **560** with the polymer layer can rotate relative the other or relative each other. In addition, the electrodes **532** and **534** can have the same proportional and configurational relationship as discussed herein (e.g., the plasma electrodes **532** being longer than the implanting electrodes **534**).

[0053] FIG. 5C next illustrates the hardened layer **518** formed over the mandrel **560** being coated with one or more layers of a second polymer material to form the catheter **500**. In one embodiment, the second polymer material can be the same type of polymer used to form the polymer layer **562** and/or a different polymer to form the polymer elongate body **502** of the catheter **500**. The polymer(s) used in the coating process can include those provided herein. Alternatively, other polymer and/or non-polymer materials can be used in coating the hardened zone **518** formed on the mandrel **560**.

[0054] In one embodiment, the coating process can be applied through an over-extrusion process. Alternatively, the coating process can be a can be a dip coating technique. Other coating processes discussed herein are also possible. The mandrel **560** can then be removed from the catheter **500** by axially stretching the mandrel **560** so as to reduce its diameter and allow it to be separated and removed from the catheter **500**.

[0055] FIG. 6A-6D provides an additional embodiment of the catheter **600** according to the present disclosure. As discussed herein, the catheter **600** illustrates an embodiment in which the hardened zone **618** is formed as a discrete layer relative the remaining portions of the catheter **600**.

[0056] As illustrated in FIG. 6A, the mandrel **660** can be coated with the layer **662** of the first polymer material, as discussed herein, by one or more of the coating techniques discussed herein. The resulting polymer layer **662** can have a thickness sufficient to allow a portion of the polymer layer **662** to be converted into the hardened zone **618** while leaving at least a portion of the polymer layer **662** between the hardened zone **618** and the mandrel **660**. Examples of suitable thicknesses include, but are not limited to, about 300 nanometers to about 600 nanometers.

[0057] FIG. 6B provides an illustration of the mandrel **660** with its polymer layer **662** after being fed through the apparatus, as discussed herein, to transform at least a portion of the polymer layer **662** into the hardened zone **618**. For the present embodiment, the ion and implant energy used with the plasma and implanting electrodes can be selected to be such that the portion of the polymer layer **662** from the exterior surface toward the mandrel **660** is transformed (e.g., carbonized) into the hardened layer **618**. As illustrated in FIG. 6B, the result is a region of the polymer layer **662** positioned between the hardened layer **618** and the mandrel **660**.

[0058] FIG. 6C next illustrates the hardened layer **618** being coated with one or more layers of the same polymer used to form the polymer layer **662** and/or a different polymer to form the polymer elongate body **602** of the catheter **600**. The polymer(s) used in the coating process can include those provided herein. Alternatively, other polymer and/or non-polymer materials can be used in coating the hardened zone **618**. In one embodiment, the coating process can be applied through one or more processes discussed herein.

[0059] A solvent can then be used to dissolve the first polymer material of the layer **662** to both expose the hardened zone **618** and release the mandrel **660** from the catheter **600**,

as illustrated in FIG. 6D. Selection of a suitable solvent will depend upon the polymer(s) used in forming the polymer layer 662.

[0060] FIGS. 7A-7D provide a further illustration of the catheter 700 according to the present disclosure. As discussed herein, the catheter 700 illustrates an embodiment in which the hardened zone 718 is formed as a non-uniform continuous layer. As illustrated in FIG. 7A, a layer 762 of a first polymer material can be deposited, as discussed herein, on the mandrel 760 as a predefined pattern 766. In one embodiment, the predefined pattern 766 can be applied using one or more of a spray coating techniques, including ink-jet coating and/or printing techniques.

[0061] For the various embodiments, the predefined pattern 766 includes a layer having different thicknesses of the layer 762 at different portions along the mandrel 760. For example, in one embodiment a series of additional "dots" of the first polymer can be added to the top of the layer 762 to form the predefined pattern 766. Other shapes, patterns and/or configurations besides dots can be used with and/or for the predefined pattern 766.

[0062] The layer 762 with its predefined pattern 766 can then be fed through the apparatus, as discussed herein, to transform at least a portion of the polymer layer 762 into the hardened zone 718. In one embodiment, the ion and implant energy used with the plasma and implanting electrodes can be selected so that only the portion of the polymer layer 762 from the exterior surface toward the mandrel 760 is transformed (e.g., carbonized) into the hardened layer 718. As illustrated in FIG. 7B, the result is a region of the polymer layer 762 positioned between the hardened layer 718 and the mandrel 760.

[0063] In addition, the apparatus 733 transforms a uniform thickness of the polymer layer 762 into the hardened zone 718. In one embodiment, transforming the uniform thickness of the polymer layer 762 into the hardened zone 718 forms pockets or divots 770 in the hardened layer 718 that mirror the predefined pattern 766. As a result, the hardened layer 718 has a pattern that is a scaled negative cast of the predefined pattern 766 applied to the polymer layer 762.

[0064] FIG. 7C next illustrates the hardened layer 718 being coated with one or more layers of the same polymer used to form the polymer layer 762 and/or a different polymer to form the polymer elongate body 702 of the catheter 700. The polymer(s) used in the coating process can include those provided herein. Alternatively, other polymer and/or non-polymer materials can be used in coating the hardened zone 718. In one embodiment, the coating process can be applied through one or more processes discussed herein.

[0065] A solvent can then be used to dissolve the first polymer material of the layer 762 to both expose the hardened zone 718 with its predefined pattern and release the mandrel 760 from the catheter 700, as illustrated in FIG. 7D. Selection of a suitable solvent will depend upon the polymer(s) used in forming the polymer layer 762.

[0066] FIGS. 8A-8D provide a further illustration of the catheter 800 according to the present disclosure. As discussed herein, the catheter 800 illustrates an embodiment in which the hardened zone 818 is formed as a non-uniform discontinuous layer. As illustrated in FIG. 8A, a predefined pattern 866 of the first polymer can be sprayed or printed onto the mandrel 860. Examples of the predefined pattern 866 include,

but are not limited to dots, lines, geometries, curves, and random patterns, among others. Use of more than one pattern is possible.

[0067] The mandrel 860 with the predefined pattern 866 of the first polymer can then be fed through the apparatus, as discussed herein, to transform the predefined pattern 866 of the first polymer into the hardened zone 818, as illustrated in FIG. 8B. The mandrel 860 with the hardened zone 818 with the predefined pattern 866 can then be being coated with one or more layers of the same polymer used to form the polymer layer 862 and/or a different polymer to form a sacrificial polymer layer 884 between the predefined pattern(s) 880 of the hardened zone 818, as illustrated in FIG. 8C.

[0068] The mandrel 860 with the hardened zone 818 in the predefined pattern 866 and the sacrificial polymer 884 can then be coated with the second polymer to form the polymer elongate body 802 of the catheter 800. The polymer(s) used in the coating process can include those provided herein. Alternatively, other polymer and/or non-polymer materials can be used in coating the hardened zone 818. In one embodiment, the coating process can be applied through one or more processes discussed herein.

[0069] A solvent can then be used to dissolve the sacrificial polymer 884 material of the layer 862 to both expose the predefined pattern 866 of the hardened zone 818 extending from the lumen surface of the polymer elongate body 802 and to release the mandrel 860 from the catheter 800, as illustrated in FIG. 8D. Selection of a suitable solvent will depend upon the polymer(s) used in forming the sacrificial polymer layer.

[0070] While the present invention has been shown and described in detail above, it will be clear to the person skilled in the art that changes and modifications may be made without departing from the spirit and scope of the invention. As such, that which is set forth in the foregoing description and accompanying drawings is offered by way of illustration only and not as a limitation. The actual scope of the invention is intended to be defined by the following claims, along with the full range of equivalents to which such claims are entitled. In addition, one of ordinary skill in the art will appreciate upon reading and understanding this disclosure that other variations for the invention described herein can be included within the scope of the present invention.

[0071] In the foregoing Detailed Description, various features are grouped together in several embodiments for the purpose of streamlining the disclosure. This method of disclosure is not to be interpreted as reflecting an intention that the embodiments of the invention require more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive subject matter lies in less than all features of a single disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description, with each claim standing on its own as a separate embodiment.

What is claimed is:

1. A catheter, comprising:

a polymer elongate catheter body having an exterior surface that extends from a first end to a second end, and a lumen surface defining a lumen and a hardened zone that extends into the polymer elongate catheter body, the hardened zone having a hardness that is greater than a hardness of the exterior surface.

2. The catheter of claim 1, where the hardened zone extends into the polymer elongate catheter body from the lumen surface a predetermined distance of 100 to 200 nanometers.

3. The catheter of claim 1, where the hardened zone has a uniform hardness value.

4. The catheter of claim 1, where the hardened zone has a hardness value that decreases in value from the lumen surface.

5. The catheter of claim 1, where the lumen surface is a carbonized region of the polymer elongate catheter body.

6. The catheter of claim 1, where the hardened zone of the lumen surface is a continuous surface.

7. The catheter of claim 1, where the hardened zone of the lumen surface has a discontinuous surface with a predefined pattern.

8. A method of modifying a lumen surface of a polymer elongate catheter body, comprising:

generating a plasma of ions inside a lumen of the polymer elongate catheter body from a first pair of electrodes positioned outside the polymer elongate catheter body; and

driving the ions of the plasma into the lumen surface of the polymer elongate catheter body with a second pair of electrodes positioned outside the polymer elongate catheter body.

9. The method of claim 8, where driving the ions of plasma into the lumen surface includes forming a hardened zone that extends into the polymer elongate catheter body.

10. The method of claim 9, including transitioning the hardened zone to a non-hardened zone of the polymer elongate catheter body.

11. The method of claim 9, including controlling a depth of the hardened zone to maintain bulk mechanical properties of the polymer elongate catheter body.

12. The method of claim 8, where driving the ions of the plasma includes alternating a negative and a positive voltage across the second pair of electrodes at a predetermined frequency.

13. The method of claim 8, including rotating the first pair and second pair of electrodes relative the polymer elongate catheter body.

14. A method of forming a catheter, comprising:
depositing a first polymer material on a mandrel;
forming a hardened zone in at least a portion of the first polymer material on the mandrel;
depositing a second polymer material over the hardened zone to form the catheter; and
removing the mandrel from the catheter.

15. The method of claim 14, where forming the hardened zone includes exposing the first polymer material to ions of a plasma to carbonize the first polymer material.

16. The method of claim 15, where exposing the first polymer material to ions of the plasma carbonizes all of the first polymer material to form the hardened zone.

17. The method of claim 15, where exposing the first polymer material to ions of the plasma carbonizes a portion of the first polymer material on the mandrel to form the hardened zone.

18. The method of claim 17, including dissolving the first polymer material to expose the carbonized layer of the hardened zone and release the mandrel from the catheter.

19. The method of claim 14, where depositing a first polymer material on a mandrel includes forming a non-uniform pattern of the first polymer material; and
dissolving the first polymer material to expose the hardened zone having the non-uniform pattern.

20. The method of claim 14, where removing the mandrel from the catheter include axially stretching the mandrel to separate the mandrel from the catheter.

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