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MICRO-FABRICATED MEDICAL DEVICE HAVING A NON-HELICAL CUT ARRANGEMENT

Abstract

The present disclosure relates to interventional devices such as catheters and guidewire devices having micro-fabricated features for providing flexibility while maintaining good torquability. An interventional device includes an elongated member having an arrangement of fenestrations which define a plurality of axially extending beams coupling a plurality of circumferentially extending rings. The fenestrations are arranged so that the resulting beams form a distributed, non-helical and non-linear pattern along the length of the elongated member. The pattern of fenestrations thereby minimizes or eliminates preferred bending axes.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a divisional of U.S. application Ser. No. 17/752,600, filed May 24, 2022, which is a divisional of U.S. application Ser. No. 16/616,139, filed Nov. 22, 2019, which is a 35 U.S.C. § 371 nationalization of PCT/US2018/034756, filed May 25, 2018, which claims priority to and the benefit of U.S. Provisional Patent Application Ser. No. 62/511,605, filed on May 26, 2017, and to U.S. Provisional Patent Application Ser. No. 62/595,425, filed on Dec. 6, 2017. Each of the foregoing applications is incorporated herein by this reference in its entirety.

BACKGROUND

[0002] Interventional devices such as guidewires and catheters are frequently utilized in the medical field to perform delicate procedures deep within the human body. Typically, a catheter is inserted into a patient's femoral, radial, carotid, or jugular vessel and navigated through the patient's vasculature to the heart, brain, or other targeted anatomy as required. Often, a guidewire is first routed to the targeted anatomy, and one or more catheters are subsequently passed over the guidewire and routed to the targeted anatomy. Once in place, the catheter can be used to deliver drugs, stents, embolic devices, radiopaque dyes, or other devices or substances for treating the patient in a desired manner.

[0003] In many applications, such an interventional device must be angled through the tortuous bends and curves of a vasculature passageway to arrive at the targeted anatomy. For example, directing a guidewire and/or catheter to portions of the neurovasculature requires passage through the internal carotid artery and other tortuous paths. Such an interventional device requires sufficient flexibility, particularly closer to its distal end, to navigate such tortuous pathways. However, other design aspects must also be considered. For example, the interventional device must also be able to provide sufficient torquability (i.e., the ability to transmit torque applied at the proximal end all the way to the distal end), pushability (i.e., the ability to transmit axial push to the distal end rather than bending and binding intermediate portions), and structural integrity for performing intended medical functions.

[0004] With respect to torquability, as a greater length of an interventional device (such as a guidewire) is passed into and through a vasculature passageway, the amount of frictional surface contact between the guidewire and the vasculature tissue increases, hindering easy movement through the vasculature passage. By transmitting torqueing forces from the proximal end to the distal end allows the guidewire to rotate and overcome the frictional forces so that further advancement and positioning is possible.

BRIEF SUMMARY

[0005] The present disclosure relates to interventional devices (such as guidewires and catheters) which have micro-fabricated features for providing flexibility while maintaining good torquability. In one embodiment, an interventional device includes an elongated member having a wall and an interior lumen. The elongated member includes a plurality of fenestrations which define a plurality of axially extending beams and a plurality of circumferentially extending rings. The beams are arranged along the length of the elongated member to form a non-helical and non-linear pattern functioning to optimally distribute bending axes to beneficially minimize or eliminate preferred bending directions of the elongated member.

[0006] Some interventional devices include cuts/fenestrations intended to increase flexibility at certain sections of the interventional device. However, typical guidewire and catheter devices

including these features end up with one or more preferred bending directions as a result of the structural arrangement and spacing of the fenestrations. Although potentially useful in some applications, preferred bending directions often have a detrimental effect on the navigation capabilities of the device. For example, in some circumstances where an operator is attempting to reach a targeted anatomical area, the preferred bending direction(s) will tend to make the device “snap” toward a preferred bending direction. If the preferred bending direction is not aligned with the desired direction of movement, it can be difficult for the operator to guide the device to the target.

[0007] Some interventional devices include fenestrations formed in a helical arrangement along a length of the device. While such helical arrangements may be more beneficial than a simple alternating cut pattern in reducing preferred bending bias, the helical arrangement can itself form undesirable preferred bending patterns within the device. For example, an interventional device having a helical cut pattern is more likely to coil or twist into a curved shape that coincides with the direction of helical rotation about the device as opposed to curving in the opposite direction. In certain anatomical circumstances, this tendency may introduce navigation difficulties and/or may inhibit the user's ability to smoothly control the device.

[0008] One or more embodiments described herein are configured with a cut pattern which effectively distributes bending bias to minimize or eliminate preferred bending directions along the length of the device. The beneficial cut patterns are arranged in a non-helical and non-linear fashion to additionally avoid the shape bias inherent in devices relying on helical or linear cut patterns.

[0009] For convenience, the present disclosure may occasionally refer to “segments” of the elongated member. As used herein, a “segment” is a repeating structural unit of the elongated member. In a typical two-beam configuration, a single segment can be defined as a first pair of opposing beams disposed between two adjacent rings (one proximal ring and one distal ring) and a second pair of opposing beams extending from the distal ring and being rotationally offset by about 90 degrees from the first pair of opposing beams. In some embodiments, rotational offsets are applied at the segment to segment level rather than at every successive beam pair.

[0010] A distributed cut pattern provides rotational offsets that optimally spread preferred bending axes using a minimal length of the elongated member and/or using a minimal number of cuts. The distributed cut pattern beneficially maximizes the likelihood that the device includes a bending axis aligned with a bend required to navigate patient vasculature. Embodiments of distributed cut patterns as disclosed herein can achieve these effects by distributing individual bending axes in many different directions using a minimal number of cuts and within a short length of the device.

[0011] For example, for a given length of the elongated member, the radial spacing/distribution of possible beam positions is maximized in as short a length as possible (i.e., in as few number of cuts as possible) while keeping successive rotational offsets within a rotational offset limit. The rotational offset limit sets a limit for the allowable rotation of a beam pair given the positions of previous beam pairs. A rotational offset limit can minimize the effects of rigid spacing artifacts in the device. In some embodiments, the rotational offset limit from one segment to the next is about 10 to 30 degrees (i.e., 10 to 30 degrees from the beam pair two pairs prior).

[0012] In some embodiments, successive segments are positioned to form an imperfect ramp pattern. An imperfect ramp pattern is formed by intentionally disrupting an otherwise helix-like pattern with a series of purposefully designed imperfections. In an imperfect ramp pattern, beams are arranged such that no set of three successive segments or beam pairs are spaced according to the same rotational offset. In other words, if the cylindrical surface of the elongated member were unrolled into a plane, no set of three segments or beam pairs would form a straight line. The imperfect ramp pattern includes a variable rotational offset that can vary from one segment to the next by 5 to 15 degrees, for example.

[0013] In some embodiments, successive beam pairs or segments are positioned to form a sawtooth

pattern. A sawtooth pattern includes a rotational offset that periodically reverses direction along the length of the elongated member. Whereas a typical helical pattern simply continues the rotational offset in the same direction through multiple rotations around the circumference of the elongated member, a sawtooth pattern reaches a first apex position before reversing direction and continuing toward a second apex position. Upon reaching the second apex position, the sawtooth pattern then reverses again and continues back toward the first apex. The pattern then repeats in this fashion along the desired length of the elongated member. In a two-beam configuration, the first and second apexes may be separated by about 90 degrees, for example.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] In order to describe the manner in which the above-recited and other advantages and features of the invention can be obtained, a more particular description of the invention briefly described above will be rendered by reference to specific embodiments thereof which are illustrated in the appended drawings. Understanding that these drawings depict only typical embodiments of the invention and are not therefore to be considered to be limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:

[0015] FIG. 1 illustrates an exemplary interventional device which may include beneficial micro-fabricated features described herein;

[0016] FIG. 2 illustrates a distal section of an exemplary guidewire device which may include beneficial micro-fabricated features described herein;

[0017] FIGS. 3A through 3C illustrate various elongated members having linear cut patterns;

[0018] FIG. 4 illustrates an elongated member having a conventional helical cut pattern;

[0019] FIG. 5 illustrates an example of an elongated member having a non-helical and non-linear cut pattern (distributed cut pattern) for beneficially distributing bending axes and minimizing or reducing preferred bending directions;

[0020] FIG. 6A illustrates exemplary beam pair positioning for forming a distributed, non-helical and non-linear cut pattern;

[0021] FIG. 6B illustrates exemplary beam pair positioning for forming an imperfect ramp cut pattern;

[0022] FIGS. 6C and 6D illustrate exemplary beam pair positioning for forming a sawtooth cut pattern; and

[0023] FIGS. 7 and 8 illustrate differences in rotational offsets, showing differences in spacing artifacts resulting from different sizes of rotational offset jumps.

DETAILED DESCRIPTION

Introduction

[0024] The present disclosure relates to interventional devices such as guidewires and catheters having micro-fabricated features which provide flexibility while also maintaining effective torquability and pushability for effective navigation through tortuous vasculature. The micro-fabricated features described herein include cut patterns which form fenestrations arranged to increase flexibility of the interventional device while maintaining good torquability and without forming preferred bending directions.

[0025] Cut patterns described herein may have different configurations defined by the number of beams resulting from each set of cuts at a given longitudinal position along the elongated member. For example, in a “two-beam” configuration, each cut location along the length of the device includes a pair of opposed cuts resulting in a pair of opposed, axially extending beams. Typically, the two beams within the resulting beam pair are symmetrically spaced about the circumference of

the elongated member (i.e., spaced 180 degrees apart). Because of this 180 degree radial symmetry, a beam pair at a zero degree position will be indistinguishable from a beam pair rotationally offset by 180 degrees. Accordingly, throughout this disclosure, the possible rotational positions for beam pairs are described as ranging from 0 to 180 degrees, with the zero and 180 degree positions being equal to one another.

[0026] While the majority of the following description will be dedicated to embodiments having a two-beam configuration, it will be understood that the same principles may also be applied to “one-beam” configurations, “three-beam” configurations, and configurations having more than three beams at each cut location. It will also be understood that in such configurations the differing angular symmetries will require some adjustments to the values used in a two-beam configuration. For example, whereas each pair of cuts in a two-beam configuration will exhibit 180 degree radial symmetry, each cut in a one-beam configuration will not exhibit radial symmetry, each trio of cuts in a three-beam configuration will exhibit 120 degree radial symmetry, each set of four cuts in a four-beam configuration will exhibit 90 degree radial symmetry, etcetera. As such, the space of possible distinguishable rotational positions in a three-beam configuration will range from 0 to 120 degrees, in a four-beam configuration will range from 0 to 90 degrees, and so on. In a one-beam configuration, the space of possible rotational positions will range from 0 to 360 degrees.

[0027] Continuing with the example of a two-beam configuration, each pair of cuts at a given cut location dictates the rotational position of the resulting beams, and the rotational position of the resulting beams dictates the preferred bending axis at that location. For a given length of the elongated member, the relative rotational positioning of successive beam pairs determines the type and magnitude of preferred bending axes throughout the elongated member.

[0028] Typically, each successive beam pair is rotated 90 degrees plus a constant modifying value from the previous beam pair. In a “linear” cut pattern, the modifying value is zero, providing a constant rotational offset of 90 degrees from one beam pair to the next along the axial length of the elongated member, meaning successive beam pairs will alternate between a zero degree position and a 90 degree rotational position. This type of cut pattern leaves the elongated member with preferred bending axes at zero and 90 degrees for the length of the elongated member. If the modifying value is 5 degrees, for example, a “helical” cut pattern with helically distributed bending axes will result.

[0029] In contrast to such linear and helical cut patterns, the embodiments described herein provide effective distribution of individual bending axes to minimize preferred bending directions in the device. This beneficially provides the device with effective navigation capabilities for navigating patient vasculature.

Overview of Interventional Devices

[0030] FIG. 1 illustrates an interventional device **100** (e.g., a catheter or guidewire device) including a handle or hub **102** and an elongated member **104**. The elongated member **104** has a proximal end **106** coupled to the hub **102** and a distal end **108** extending away from the hub **102**. The hub **102** may include paddles, handles, grips, or the like allowing a user to grasp the device, rotate, push/pull, and otherwise manipulate the device **100**. The elongated member **104** may be formed as a guidewire or as a catheter. Some embodiments such as guidewires may omit the hub **102** and may be used with accessories such as a torque device.

[0031] The elongated member **104** includes a plurality of fenestrations cut into its outer surface. The fenestrations may be formed by cutting one or more pieces of stock material to form a cut pattern which leaves the fenestrations. The fenestrations can provide a variety of benefits, including increasing the flexibility/bendability of the elongated member **104**. In some embodiments, the fenestrations are arranged to provide enhanced flexibility (relative to a similar section of stock material lacking fenestrations) while maintaining sufficient outer circumferential structure for transmitting torque and thereby maintaining good torquability of the elongated member **104**.

[0032] The elongated member **104** may be any length necessary for navigating a patient's anatomy

to reach a targeted anatomical area. A typical length may be within a range of about 50 to 300 cm, for example. In a catheter embodiment, the outer diameter of the elongated member **104** may be within a range of about 0.010 inches to about 0.150 inches, though larger or smaller diameters may also be utilized according to preferences and/or application needs. In a guidewire embodiment, the outer diameter of the elongated member **104** may be about 0.014 inches, or may be within a range of about 0.008 to 0.145 inches, though larger or smaller sizes may also be utilized according to user preferences and/or application needs.

[0033] The elongated member **104**, in a catheter embodiment, is typically formed from a material having an elastic modulus of about 3000 MPa to about 4500 MPa, or about 3500 MPa to about 4000 MPa. In one exemplary embodiment, the elongated member **104** is formed from or includes polyether ether ketone (PEEK). Other polymers with higher moduli may also be utilized where cost and/or fabrication considerations warrant it. In some embodiments, the elongated member **104** includes or is formed from a nickel-titanium alloy having superelastic properties at body temperature. In some embodiments, a proximal portion of the elongated member **104** is formed from a stainless steel or other material with similar stress-strain and elastic modulus properties. Typically, if the elongated member **104** is formed from two or more different materials, the higher modulus material(s) are used at more proximal sections and the lower modulus material(s) are used at more distal sections.

[0034] FIG. **2** illustrates the distal end of an embodiment of an interventional device configured as a guidewire **200**. The embodiment illustrated in FIG. **2** may represent the distal end **108** of a guidewire embodiment of the elongated member **104** of FIG. **1**. The illustrated guidewire **200** includes a core **212** and a tube structure **214** coupled to the core **212**. As shown, a distal section **221** of the core **212** extends into the tube **214** and is surrounded by the tube **214**. In some embodiments, the distal section **221** of the core **212** is ground so as to progressively taper to a smaller diameter (e.g., about 0.002 inches) at the distal end. The distal section **221** of the core **212** may have a round cross-section, rectangular cross-section, or other suitable cross-sectional shape. In this example, the core **212** and the tube **214** have substantially similar outer diameters at the attachment point **213** where they adjoin and attach to one another.

[0035] The tube **214** is coupled to the core **212** (e.g., using adhesive, soldering, and/or welding) in a manner that allows torsional forces to be transmitted from the core **212** to the tube **214** and thereby to be further transmitted distally by the tube **214**. A medical grade adhesive **220** may be used to couple the tube **214** to the core **212** at the distal end of the device and to form an atraumatic covering.

[0036] The guidewire **200** may also include a coil **224** disposed within the tube **214** so as to be positioned between an outer surface of the distal section of the core **212** and an inner surface of the tube **214**. The coil **224** may be formed from a radiopaque material, such as platinum. The illustrated coil **224** is formed as one integral piece. In alternative embodiments, the coil **224** includes a plurality of separate sections stacked, positioned adjacent to one another, and/or interlocked through intertwining.

[0037] The tube **214** includes micro-fabricated fenestrations configured to provide effective flexibility and torquability of the interventional device without forming preferred bending directions. Some embodiments may additionally or alternatively include cuts formed in the core **212** itself, such as along the distal section **221** of the core.

Cut Patterns

[0038] FIGS. **3A** through **3C** illustrate embodiments of linear cut patterns, with FIG. **3A** showing a typical “two-beam” linear cut pattern, FIG. **3B** showing a typical “one-beam” linear cut pattern, and FIG. **3C** showing a typical “three-beam” linear cut pattern.

[0039] As shown in FIG. **3A**, the elongated member **600** includes a plurality of axially extending beams **632** and circumferentially extending rings **634**. The elongated member **600** has a two-beam cut pattern because two circumferentially opposing beams **632** are disposed between each pair of

adjacent rings **634**. The illustrated cut pattern is a linear cut pattern because no rotational offset is applied from one segment to the next.

[0040] As described above, a “segment” is a repeating structural unit of the elongated member. In some embodiments, a single segment can be defined as a first pair of opposing beams **632** disposed between two adjacent rings **634** (one proximal ring and one distal ring) and a second pair of opposing beams **632** extending from the distal ring and being rotationally offset by about 90 degrees from the first pair of opposing beams **632**. The linear arrangement of segments results in the formation of preferred bending directions aligned to the fenestrations of the elongated member **600**.

[0041] FIG. **3B** illustrates an elongated member **900** having a plurality of beams **932** and rings **934**. The elongated member **900** is an example of a one-beam cut pattern because a single beam **932** is disposed between each pair of adjacent rings **934**. In such a one-beam cut pattern, a single segment may be defined as a first beam **934** disposed between two adjacent rings **934** (one proximal ring and one distal ring) and a second beam **932** extending from the distal ring and being rotationally offset by about 180 degrees from the first beam **932**. As with the elongated member **600**, the elongated member **900** has a linear cut pattern because no rotational offset is applied from one segment to the next.

[0042] FIG. **3C** illustrates an elongated member **1000** having a plurality of beams **1032** and rings **1034**. The elongated member **1000** is an example of a three-beam cut pattern because three beams **1032** are disposed between each pair of adjacent rings **1034**. In such a three-beam cut pattern, a single segment may be defined as a first triplicate of beams **1032** disposed between two adjacent rings **1034** (one proximal ring and one distal ring) and a second triplicate of beams **1032** extending from the distal ring and being rotationally offset by about 60 degrees from the first triplicate. As with the elongated members **600** and **900**, the elongated member **1000** has a linear cut pattern because no rotational offset is applied from one segment to the next.

[0043] From the foregoing examples it will be understood that a variety of cut patterns may be utilized. For example, cut patterns providing more than three beams between each pair of adjacent rings may be utilized according to particular application needs. Generally, the higher the number of beams left between each pair of adjacent rings, the relatively greater the stiffness of the elongated member.

[0044] FIG. **4** illustrates an embodiment of a typical helical cut pattern intended to minimize preferred bending directions in a micro-fabricated guidewire or catheter device. As shown, cuts made to the elongated member **300** leave pairs of opposing beams situated on opposing sides of the longitudinal axis of the hollow member. Each pair of such cuts forms two beams **332** (extending substantially axially) connecting adjacent rings **334** (extending substantially transversely and circumferentially).

[0045] A rotational offset is applied at each successive segment of the elongate member **300** to form the helical pattern. As used herein, a “rotational offset” is the angular rotation between two adjacent segments. A rotational offset is therefore applied from one segment to the next, even though individual cuts within a segment may also be offset from one another.

[0046] In a typical embodiment, a single segment can be defined as a first pair of opposing beams **332** disposed between two adjacent rings **334** (one proximal and one distal) and a second pair of opposing beams **332** extending from the distal ring and being rotationally offset by about 90 degrees from the first pair of opposing beams **332**. The cuts are arranged to form a substantially consistent rotational offset from one segment to the next. For example, the illustrated embodiment shows a rotational offset of about 5 degrees from one segment to the next. When multiple successive segments having such an angular offset are formed, the resulting pattern of beams along a sufficient length of the elongated member **300** wraps around the axis of the elongated member **300** in a continuously rotating helical pattern.

[0047] This type of helical arrangement may also be used in embodiments having different cut

patterns. For example, an elongate member having a “one-beam” or “bypass” cut pattern where each cut leaves a single beam between each set of adjacent rings may have a constant rotational offset between each successive cut or set of cuts.

[0048] A helical arrangement may also be applied to an embodiment having more than a two-beam cut pattern. For example, the same helix-forming rotational offset may be applied to a three-beam embodiment (such as shown in FIG. 3C) or to an embodiment having more than three beams between adjacent rings.

[0049] Helical cut patterns such as that shown in FIG. 4 can beneficially minimize some of the preferred directional bending tendencies of an elongate member. However, the helical structure itself defines a preferred bending curve. An elongated member having a helical cut pattern is more likely to coil or twist into a curve that coincides with the direction of helical rotation as opposed to curving in the opposite direction.

Distributed Patterns

[0050] FIG. 5 illustrates a section of an elongated member **500** with a distributed cut pattern. The cuts are beneficially arranged to efficiently distribute the rotational spacing of each beam pair. In this manner, the non-helical and non-linear cut pattern effectively eliminates or minimizes preferred bending directions along the length of the elongated member **500**. The cut pattern shown in FIG. 5 is “non-helical” because, in contrast to a helical cut pattern, the resulting beams of the elongated member **500** are not arranged in a helical pattern around axis of the elongated member **500**.

[0051] The cut pattern shown in FIG. 5 is also “non-linear” because there is a rotational offset applied at successive segments of the device, and because the rotational offsets applied to the segments making up the elongated member **500** are not necessarily equal or constant from one segment to the next.

[0052] A helix is commonly defined as following a curve on a conical or cylindrical surface that would become a straight line if the surface were unrolled into a plane. Using the helical cut pattern shown in FIG. 4 as an example, any curved lines tracing the arrangement of the beams/segments along the length of the elongated member **300** would form straight lines if the elongated member **300** were cut open and “unrolled” into a plane. In contrast, using the cut pattern illustrated in FIG. 5, any lines tracing the arrangement of the beams/segments along the length of the elongated member **500** would not form straight lines. For example, given a set of any three successive beam pairs or segments along the length of the elongated member **500** of FIG. 5, the rotational positions of the three successive beam pairs or segments would not form a straight line if the elongated member **500** were unrolled into a plane.

[0053] A helix is also typically understood to require at least one full circumferential rotation about the conical/cylindrical surface it lies upon. As such, a cut pattern may also be considered non-helical where the resulting rotational arrangement of beam pairs or segments does not form a pattern that fully wraps around the circumference of the elongated member at least once before changing direction. For example, if the cylindrical surface of the elongated member were unrolled into a plane, and that plane included a series of three or more segments positionally aligned in a straight line, the series of segments would still not constitute a helix if the straight line does not wrap around the circumference of the elongated member at least once.

[0054] Rotational offsets may be applied from one beam pair to the next. Alternatively, rotational offsets may be applied to the elongated member at the segment to segment level. As described above, each segment of the elongated member may be defined as a first pair of opposing beams between a proximal and distal ring, and a second pair of beams extending from the distal ring which are offset by approximately 90 degrees from the first pair of beams. Alternative embodiments may apply the distributed rotational offset pattern between segments of different sizes and/or between segments with different internal offsets. For example, some embodiments may include segments having more than two pairs of beams (and more than two corresponding

rings) and/or with internal offsets different than 90 degrees. Further, even though the illustrated example shows a two-beam cut pattern where each pair of the opposing cuts results in two circumferentially opposing beams, it will be understood that the distributed offset patterns may also be applied to one-beam cut patterns (see FIG. 3B), three-beam cut patterns (see FIG. 3C), and patterns having more than three beams between adjacent rings.

[0055] FIG. 6A graphically compares one example of a distributed arrangement with a conventional helical arrangement. As shown, the helical cut pattern applies a constant rotational offset from segment to segment along the length of the elongated member. The distributed cut pattern applies a rotational offset that effectively distributes bending axes without relying on a helical pattern.

[0056] Given a starting beam pair arbitrarily assigned to a zero degree position, successive beam pairs are rotationally offset to maximize the radial distribution of beam positions across the available 180 degree radial space as quickly as possible (i.e., in as few cuts as possible). However, in the illustrated embodiment, a rotational offset limit is also applied to prevent the formation of rigid spacing artifacts (discussed further below with respect to FIGS. 7 and 8).

[0057] The rotational offset limit defines a limit on the acceptable rotational “jump” from one beam pair to the next or from one segment to the next. A rotational offset limit with a value of about 10 to 30 degrees from one segment to the next, or a rotational offset limit that rotates successive beam pairs by $90 \text{ degrees} \pm \text{that value}$, has been shown to provide effective distribution of bending axes without causing overly rigid spacing artifacts. For example, the rotational offset limit may restrict rotation from one beam pair to the next to a value within a range of about 60 to 120 degrees, or about 70 to 110 degrees, or about 80 to 100 degrees. Other embodiments may utilize other rotational offset limits, or may even omit the rotational offset limit, depending on particular product and/or application needs. For example, the rotational offset limit may be raised to a value higher than 30 degrees if the resulting spacing artifacts are acceptable for a particular application.

[0058] The exemplary distributed cut pattern illustrated in FIG. 6A utilizes a rotational offset limit of 30 degrees. As shown, a first beam pair is positioned at an arbitrary 0 degree position, and the second beam pair is positioned at 90 degrees. The greatest remaining gaps in the available 180 degree space are between 0 and 90 degrees and between 90 and 180 degrees (where 0 and 180 degrees represent the same position). Placing the next beam pair near a midpoint of one of these gaps, such as at 45 degrees, would best distribute the bending axes of the device. However, placing the next beam pair at 45 degrees would violate the rotational offset limit of 30 degrees. The next beam pair is therefore placed to be close to the midpoint of a remaining gap without violating the rotational offset limit. In this example, the third beam pair is placed at 30 degrees. The fourth beam pair is placed at 120 degrees, which is 90 degrees from the third beam pair. In this particular example, every other beam pair is offset 90 degrees from the previous. Alternative embodiments need not necessarily follow this particular pattern.

[0059] Continuing with the example distribution of FIG. 6A, the largest remaining positional gaps are now between 30 and 90 degrees and between 120 and 180 degrees. The fifth and sixth beam pairs are placed at 60 and 120 degrees, respectively. The remaining positional gaps are now located every 30 degrees (i.e., between 0 and 30 degrees, between 30 and 60 degrees, between 60 and 90 degrees, etc.). As the pattern continues, remaining angular positions are filled in a manner that radially spaces beam pairs as fast as possible without violating the rotational offset limit.

[0060] In the illustrated example, the available angular positions are provided at a granularity of 10 degrees. In other words, all angular positions may be considered as filled when each 10 degree increment has been filled. The illustrated pattern may therefore include beam pairs positioned at approximately every 10 degree position before resetting. Such an arrangement is referred to herein as having a “positional granularity” of 10 degrees. Alternative embodiments may utilize a different positional granularity, such as a granularity of 0.1, 0.5, 1, 3, 5, 10, 15, 18, 20, 25, or 30 degrees, for example.

[0061] The exact positioning illustrated may be adjusted, and it will be understood that the pattern shown in FIG. 6A is illustrative only. For example, the positional gaps may be filled using a different particular sequence as long as rotational jumps are within the predetermined rotational offset limit. Preferably, when filling in gaps between rotational positions, the next beam pair is positioned to be close to the approximate center of the largest remaining positional gap without violating the rotational offset limit. For example, where a gap exists between the zero degree position and the 30 degree position, the segment may be positioned at the 10 to 20 degree position. [0062] Further, alternative embodiments may utilize a positional granularity that fills in positions of more or less than 10 degrees. Where fewer segments are used before resetting the pattern, the size range of each suitable position will be larger, and where more segments are used before resetting the pattern, the size ranges will become smaller. Some embodiments may include about 6 to 36 beam pairs, or about 10 to 18 beam pairs, before the availability of filled angular positions within the 180 degree radial space is reset. Other embodiments may include many more beam pairs before available positions are reset. As the predetermined positional granularity is lowered, the number of beam pairs needed to fill all available angular positions will rise. Thus, a device having a positional granularity of 1 degree will use 180 beam pairs to fill 180 available angular positions. Moreover, because there are multiple ways of filling available angular positions according to the predetermined parameters (e.g., positional granularity and rotational offset limit) of the selected distributed pattern, the distributed cut pattern need not identically repeat itself after resetting. Therefore, as used herein, the terms “reset,” “resetting,” and the like refer to resetting the availability of angular positions within the 180 degree radial space after it has been filled by beam pairs, and the terms do not necessarily imply that the subsequent refilling of angular positions along the next section of the elongated member will exactly repeat the previous pattern. Indeed, in at least some embodiments, the entire length of the distributed pattern may be non-repeating.

[0063] It will be understood that the foregoing principles may also be applied to an embodiment having a one-beam arrangement, an embodiment having a three-beam arrangement, or an embodiment having more than a three-beam arrangement. For example, the one-beam embodiment shown in FIG. 5 may be modified to follow a non-helical and non-linear cut pattern rather than the helical cut pattern shown. The same principles described above may be applied to a one-beam embodiment, except that the range of angular positions to fill extends to 360 degrees. Likewise, the same principles may be generally applied to a three-beam embodiment, except that the range of angular positions to fill extends to 120 degrees.

Imperfect Ramp Patterns

[0064] FIG. 6B graphically illustrates another embodiment of a non-helical cut pattern formed by intentionally disrupting an otherwise helical pattern with a series of purposefully designed imperfections. This type of cut pattern is referred to herein as an “imperfect ramp” pattern. The intentional divergences of an imperfect ramp pattern beneficially function to reduce or prevent preferred torsional and curvature relics inherent in a true helical arrangement. As shown, segments are arranged such that no three successive beam pairs or segments are spaced according to the same rotational offset. In other words, no three beam pairs or segments are arranged so as to form a straight line if the cylindrical elongated member were unrolled into a plane.

[0065] In contrast to the imperfect ramp patterns of FIG. 6B, a true helical pattern is typically formed by rotationally offsetting each successive segment or each successive beam pair by a constant value. For example, a true helical pattern in a two-beam structure may be formed by rotationally offsetting each successive cut pair by a constant value of 5 degrees, 85 degrees, 95 degrees, or some other constant value that is not a multiple of 90 degrees.

[0066] In an imperfect ramp cut pattern, the modifying value is intentionally made variable rather than constant. For example, as in FIG. 6B, an imperfect ramp pattern may be formed by rotationally offsetting each successive beam pair by a constant value \pm a variable modifying value. A rotational offset that includes a constant value \pm a variable modifying value is referred to herein as

an “imperfect rotational offset.”

[0067] The variable modifying value may range from 5 to 15 degrees. In other embodiments, the variable modifying value may range from 2.5 to 30 degrees, or some other range suitable for the intended purpose of the resulting device. The variable modifying value is preferably randomly selected at each segment or beam pair to which it is applied, with upper and lower bounds of the random selection being defined by the modifying value range (e.g., 5 to 15 degrees). The constant value portion of the offset is typically 180 degrees in a one beam pattern, 90 degrees in a two-beam pattern, 60 degrees in a three-beam pattern, etcetera.

[0068] Alternative embodiments may apply the imperfect ramp pattern between segments of different sizes and/or between segments with different internal offsets. For example, some embodiments may include segments having more than two pairs of beams (and more than two corresponding rings) and/or with internal offsets different than 90 degrees. Further, even though the illustrated example shows a two-beam cut pattern where each pair of the opposing cuts results in two circumferentially opposing beams, it will be understood that the distributed offset patterns may also be applied to one-beam cut patterns (see FIG. 3B), three-beam cut patterns (see FIG. 3C), and patterns having more than three beams between adjacent rings.

Sawtooth Patterns

[0069] FIG. 6C illustrates another embodiment of a non-helical cut pattern referred to herein as a “sawtooth” pattern. As with other non-helical cut patterns described herein, the sawtooth cut pattern can beneficially avoid preferred bending axes while also limiting preferred curvature directions inherent in helical patterns. In contrast to a helical pattern, a sawtooth cut pattern periodically reverses the direction of the rotational offset.

[0070] Both the sawtooth pattern and the helical pattern of FIG. 6C have an angular offset of about 10 degrees between adjacent segments, with each cut pair within each segment offset by 90 degrees. Whereas the helical pattern simply continues with these offset values in the same direction through multiple rotations around the circumference of the elongated member, the sawtooth pattern reaches a first apex position before reversing direction and continuing toward a second apex position. Upon reaching the second apex position, the sawtooth pattern then reverses again and continues back toward the first apex. The pattern then repeats along the desired length of the elongated member.

[0071] For example, the first apex position is set at about 90 degrees (i.e., 90 degrees for the first cut pair of the segment and 180 degrees for the second cut pair of the segment). Upon reaching the first apex position, the pattern reverses toward the second apex position. In this embodiment, the second apex position is set at about 0 degrees (i.e., 0 degrees for the first cut pair of the segment and 90 degrees for the second cut pair of the segment). Alternative embodiments may include other apex positions. Given an arbitrary zero degree starting position, the first apex position is less than 360 degrees in a one-beam configuration, less than 180 degrees in a two-beam configuration, less than 120 degrees in a three-beam configuration, and so on. Preferably, the first apex position is about 180 degrees for a one-beam configuration, 90 degrees for a two-beam configuration, 60 degrees for a three-beam configuration, and so on.

[0072] As described above, the angular offset from segment to segment in the sawtooth pattern of FIG. 6C is about 10 degrees. In other embodiments of sawtooth cut patterns, the angular offset may be more or less than 10 degrees, such as from about 5 degrees to about 30 degrees. Additionally, or alternatively, portions of the cut pattern between the apexes may include a variable offset. For example, one or more portions between the apexes may include an imperfect rotational offset such as described above. FIG. 6D illustrates one such embodiment. The sawtooth cut pattern shown in FIG. 6D follows a sawtooth pattern similar to the pattern shown in FIG. 6C, but also includes some sections of variable/imperfect rotational offset between the apexes.

[0073] Alternative embodiments may apply the sawtooth pattern between segments of different sizes and/or between segments with different internal offsets. For example, some embodiments

may include segments having more than two pairs of beams (and more than two corresponding rings) and/or with internal offsets different than 90 degrees. Further, even though the illustrated example shows a two-beam cut pattern where each pair of the opposing cuts results in two circumferentially opposing beams, it will be understood that the distributed offset patterns may also be applied to one-beam cut patterns (see FIG. 3B), three-beam cut patterns (see FIG. 3C), and patterns having more than three beams between adjacent rings.

Spacing Artifacts

[0074] FIG. 7 illustrates an example of an undesirable spacing artifact that may result where a rotational offset limit is not applied. FIG. 7 illustrates a section of an elongated member **700** having a first segment **750a** and a second segment **750b**. The first segment **750a** includes a first pair of beams **730a** (only one of which is visible in this view) and second pair of beams **730b** and **730c** which are offset from the first pair by 90 degrees. The second segment **750b** includes a first pair of beams **730d** and **730e**, and a second pair of beams **730f** and **730g** which are offset from the first pair by 90 degrees. Each beam within a pair is circumferentially spaced from its corresponding beam by 180 degrees. The second segment **750b** is offset from the first segment **750a** by 45 degrees, which positions the first pair of beams **730d** and **730e** off by 45 degrees from the first pair of beams **730a** and positions the second pair of beams **730f** and **730g** off by 45 degrees from the second pair of beams **730b** and **730c**.

[0075] Applying such a 45 degree offset from the first segment **750a** to the second segment **750b** is desirable because it places the bending axes of the second segment **750b** in between the bending axes of the first segment **750a**. However, the 45 degree jump also results in beam spacing between segments which can leave an overly rigid artifact in a portion of the elongated member **700**. In the illustrated member **700**, the beam **730d** is only spaced from the beam **730b** by 45 degrees, whereas the beam **730e** is spaced from the beam **730b** by 135 degrees. Likewise, the beam **730e** is only spaced from the beam **730c** by 45 degrees, whereas the beam **730d** is spaced from the beam **730c** by 135 degrees. This disproportionate spacing may be undesirable because the region of the elongated member **700** having the smaller spacing may be overly rigid and/or the region having the larger spacing may be overly flexible.

[0076] In contrast, a more limited jump in the rotational offset applied from one segment to the next will minimize the discrepancy in beam spacing between segments. For example, FIG. 8 illustrates a section of an elongated member **800** with a more limited rotational offset of about 20 degrees applied between a first segment **850a** and a second segment **850b**. As in the elongated member **700** of FIG. 7, the first segment **850a** includes a first pair of beams **830a** and a second pair of beams **830b** and **830c**, and the second segment **850b** includes a first pair of beams **830d** and **830e** and a second pair of beams **830f** and **830g**. However, because the second segment **850b** is offset from the first segment **850a** by a more limited 20 degrees, the spacing discrepancy between beams **830b**, **830c**, **830d**, and **830e** is less pronounced. Beam **830d** is spaced 70 degrees from beam **830b**, and beam **830e** is spaced 110 degrees from beam **830b**. Likewise, beam **830e** is spaced 70 degrees from beam **830c** and beam **830d** is spaced 110 degrees from beam **830c**. Thus, although a spacing discrepancy still exists between segments, it may be controlled to a suitable degree by providing an appropriate rotational offset limit.

[0077] The terms “approximately,” “about,” and “substantially” as used herein represent an amount or condition close to the stated amount or condition that still performs a desired function or achieves a desired result. For example, the terms “approximately,” “about,” and “substantially” may refer to an amount or condition that deviates by less than 10%, or by less than 5%, or by less than 1%, or by less than 0.1%, or by less than 0.01% from a stated amount or condition.

[0078] The present invention may be embodied in other forms, without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended

claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

Claims

- 1.** An interventional device, comprising: an elongated member having a wall and an interior lumen, the elongated member including a plurality of fenestrations extending through the wall and exposing the lumen, the plurality of fenestrations defining a plurality of axially extending beams and a plurality of circumferentially extending rings arranged in a distributed pattern, wherein the distributed pattern includes a first beam pair of the elongated member defined as being positioned at a zero degree position, and wherein successive beam pairs are rotationally offset from the first beam pair to maximize the radial distribution of beam positions without surpassing a rotational offset limit, the rotational offset limit limiting the allowable rotation from one segment to the next.
 - 2.** The device of claim 1, wherein the rotational offset limit restricts the rotational offset from one beam pair to the next to a value of about 60 to 120 degrees.
 - 3.** The device of claim 1, wherein the rotational offset limit restricts the rotational offset from one beam pair to the next to a value of about 70 to 110 degrees.
 - 4.** The device of claim 1, wherein the rotational offset limit restricts the rotational offset from one beam pair to the next to a value of about 80 to 100 degrees.
 - 5.** The device of claim 1, wherein successive beam pairs are positioned near the midpoint of a largest remaining positional gap without surpassing the rotational offset limit, such as being positioned as close to the midpoint of a largest remaining positional gap as the rotational offset limit allows.
 - 6.** The device of claim 1, wherein the distributed pattern has a positional granularity of about 1 to 30 degrees or about 0.1 degree to 30 degrees.
 - 7.** The device of claim 1, wherein the interventional device is a micro-catheter device or a guidewire device.
 - 8.** The device of claim 7, wherein the interventional device is a guidewire that includes a core, and wherein the elongated member is formed as a tube structure coupled to the core such that a distal section of the core passes into at least a portion of the tube structure.
 - 9.** The device of claim 8, further comprising one or more coils disposed within the tube structure so as to be positioned between an outer surface of the distal section of the core and an inner surface of the tube structure.
 - 10.** The device of claim 8, wherein the core is formed from stainless steel or nitinol.
 - 11.** The device of claim 8, wherein the tube structure is formed from nitinol.
 - 12.** The device of claim 8, wherein the fenestrations are arranged in one or more of a one-beam, two-beam, or three-beam pattern.
 - 13.** The device of claim 8, wherein the elongated member is formed from a succession of segments, each segment including a first pair of circumferentially opposed beams and a second pair of circumferentially opposed beams which are rotationally offset by about 90 degrees from the first pair of beams.
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