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(54) **ARROW OR CROSSBOW BOLT SHAFTS HAVING A PROFILED INNER DIAMETER**

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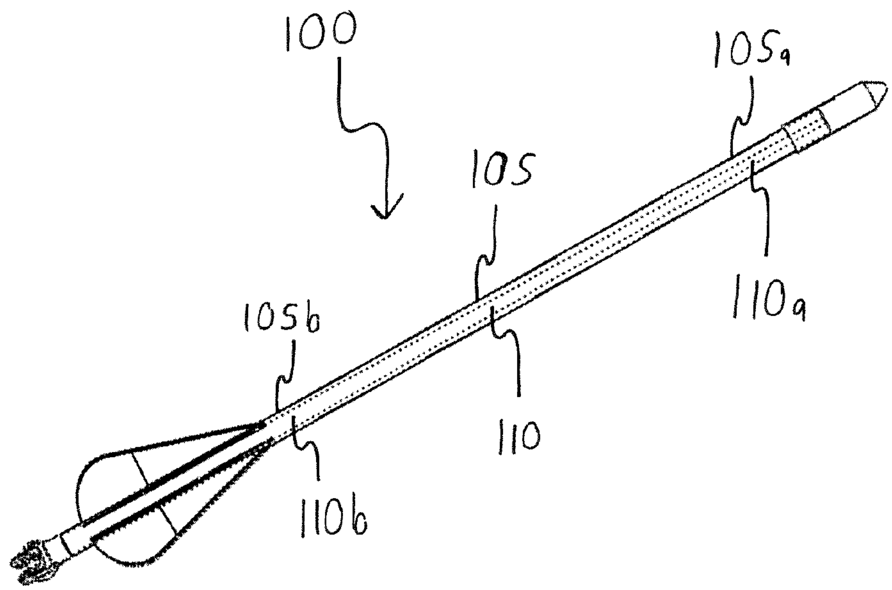
(52) **U.S. Cl.**

CPC ***F42B 6/04*** (2013.01); ***F42B 10/02*** (2013.01)

(57) **ABSTRACT**

Composite arrow or crossbow bolt shafts have a hollow core, where the inner diameter of the shafts vary along the length of the shaft, but the outer diameter of the shafts remains constant. The hollow inner core may vary gradually in size along the length of the shaft, or it may vary in discrete stepped portions so that the shaft is more hollow in some portions in comparison to others. The hollow composite shafts may be manufactured by wrapping a tapered or stepped inner mandrel with fibers of a composite material and curing that composite material, or by triaxially braiding composite fibers around a tapered or stepped inner mandrel before curing those composite fibers.



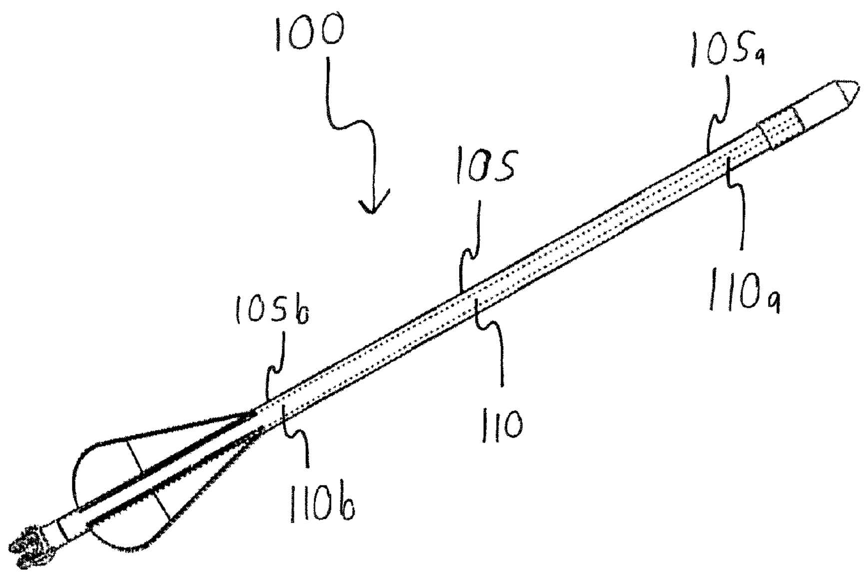


FIG. 1A

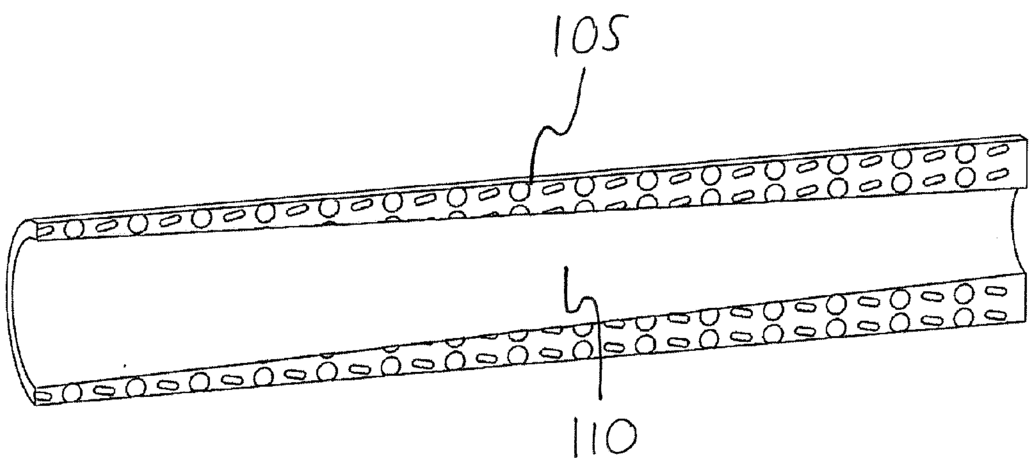


FIG. 1B

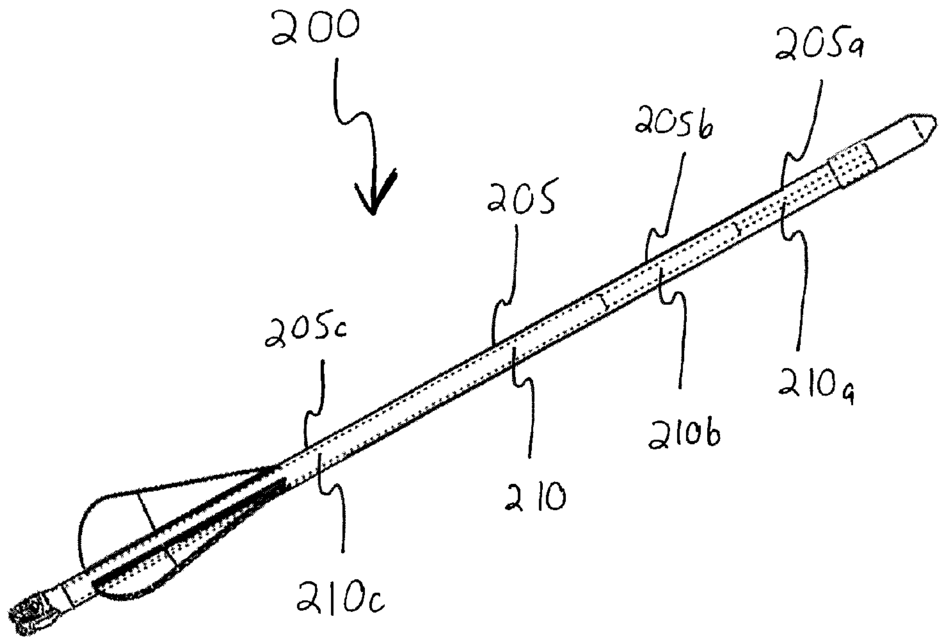

200
205a
205b
205
205c
210a
210b
210
210c

FIG. 2A

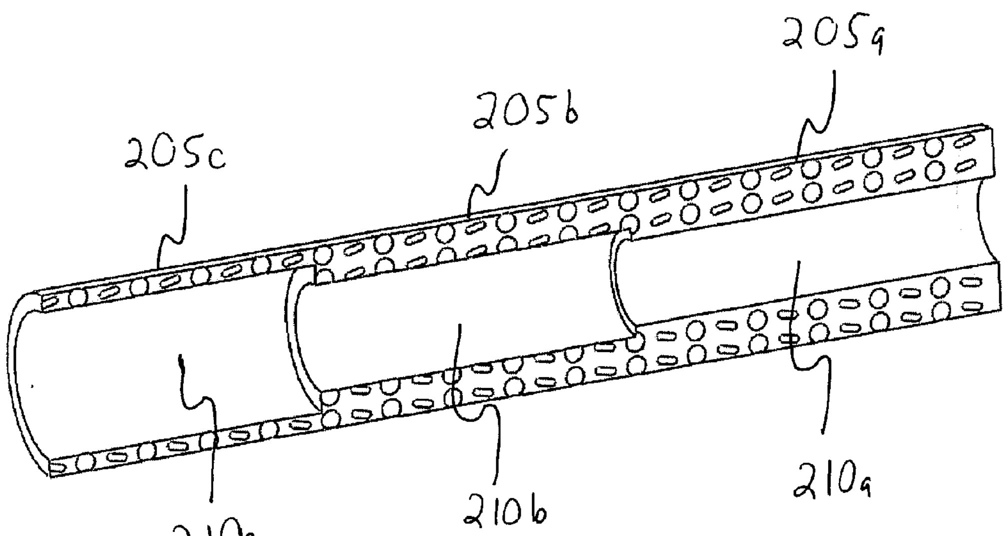

205a
205b
205c
210a
210b
210c

FIG. 2B

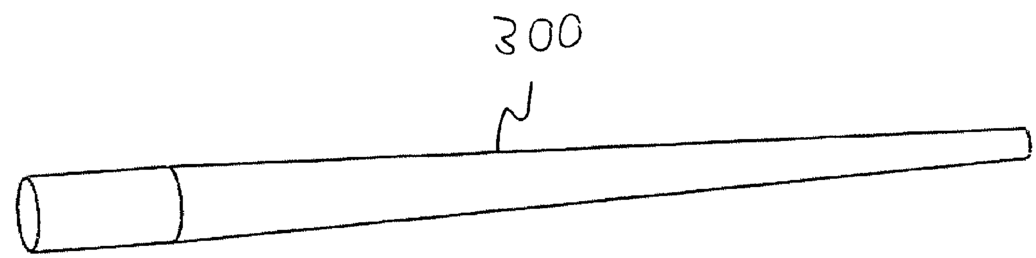


FIG. 3A

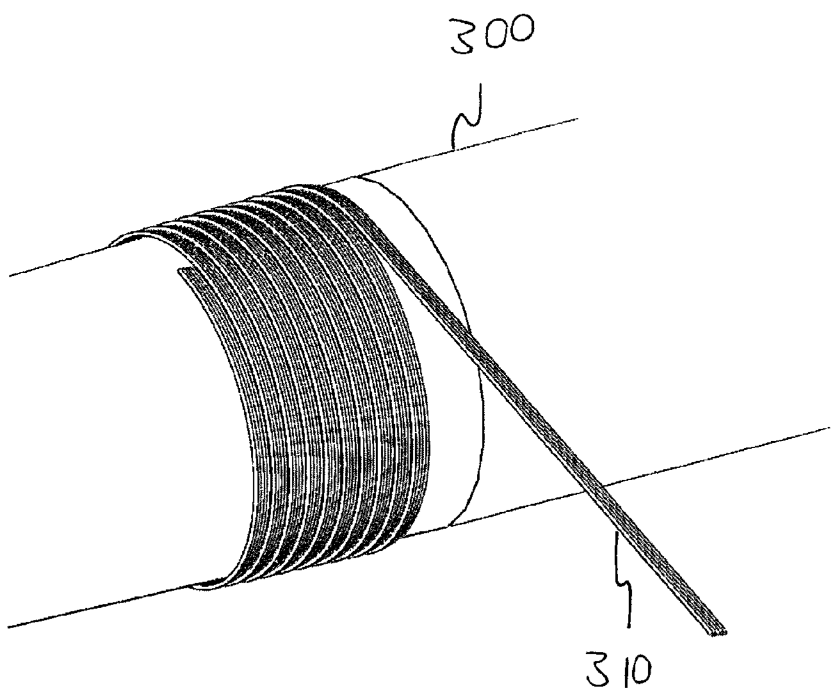


FIG. 3B

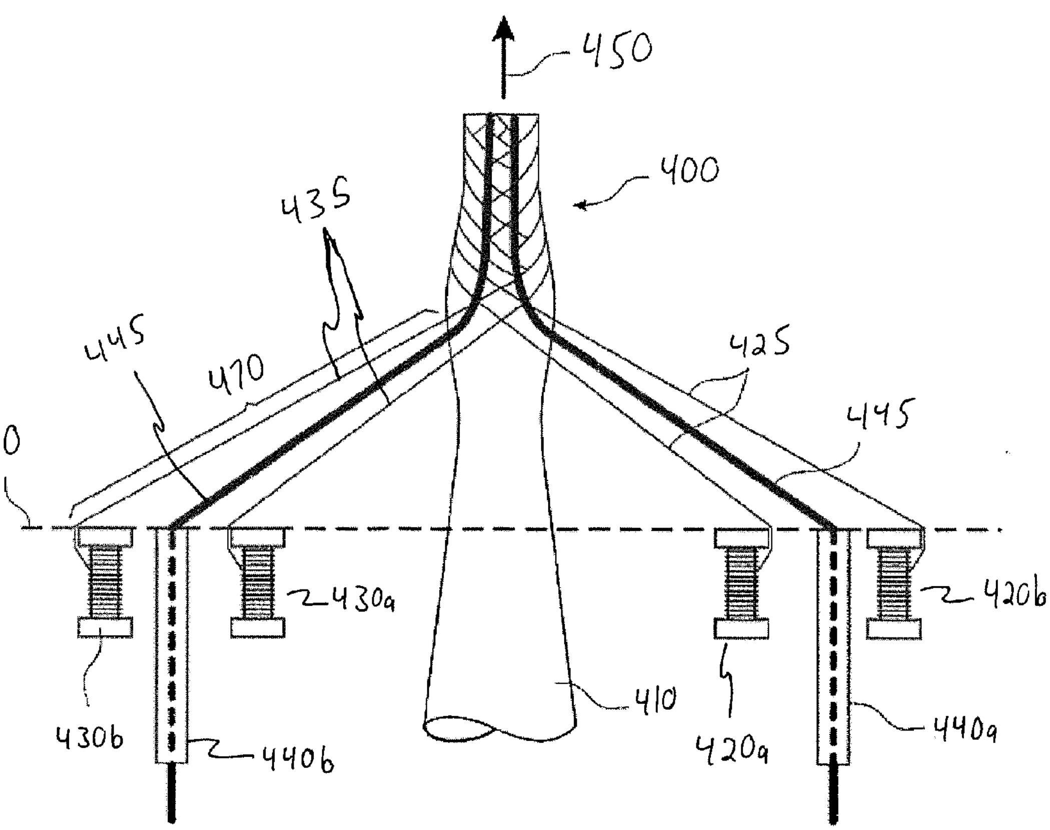

450
400
435
445
470
425
445
460
430a
420b
430b
440b
410
420a
440a

FIG. 4

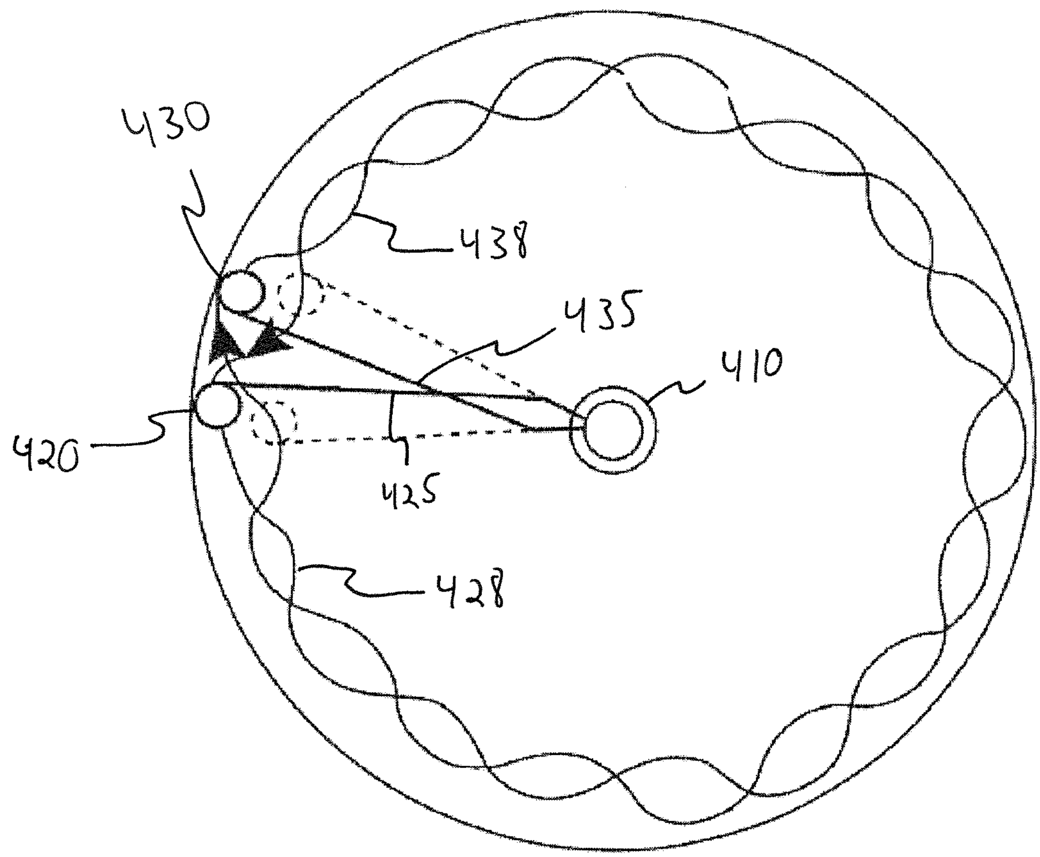


FIG. 5

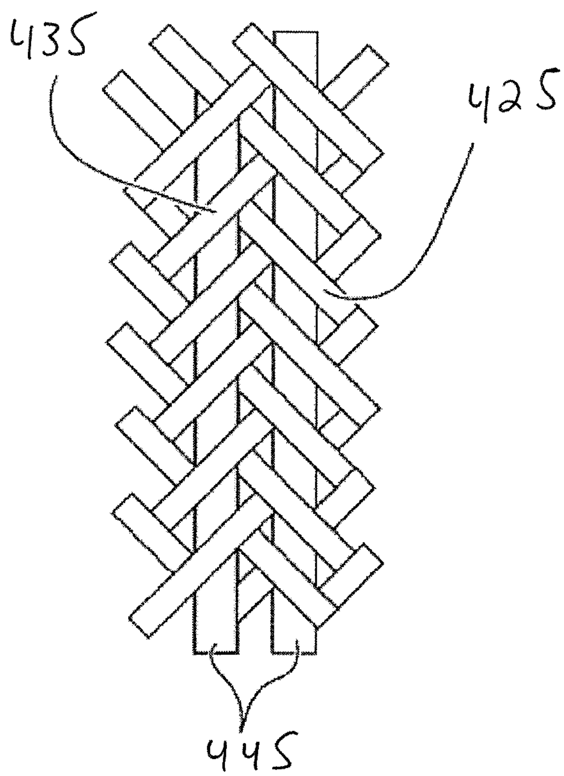


FIG. 6

ARROW OR CROSSBOW BOLT SHAFTS HAVING A PROFILED INNER DIAMETER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/208,220 filed Aug. 21, 2015, which is hereby incorporated by reference in its entirety.

FIELD OF EMBODIMENTS OF THE PRESENT INVENTION

[0002] Embodiments of the present invention relate to arrow or crossbow bolt shafts, collectively referred to as "shafts," having a profiled inner diameter, as well as methods of manufacturing such shafts. More particularly, the present invention is directed to shafts with a hollow core and a varying inner diameter, and methods of manufacturing such shafts.

BACKGROUND OF EMBODIMENTS OF THE INVENTION

[0003] Arrows and crossbow bolts with composite carbon shafts have recently become increasingly popular. Commonly, such composite shafts are manufactured around an inner core—a metal rod known as an "inner mandrel." The inner mandrel is a metal rod or cylinder typically made from steel or aluminum, and has a uniform, smooth outer diameter. These composite shafts are often made of materials such as carbon fiber—usually, a carbon fiber sheet or mat that is impregnated with a resin and then wrapped around the metal inner mandrel.

[0004] After being wrapped around the inner mandrel, the carbon fiber sheet can be itself wrapped with a polymer, such as nylon or polypropylene, to hold the carbon fiber sheet in place during manufacture. The wrapped inner mandrel is then cured in an oven, which liquefies the resin and bonds the carbon fibers, forming the composite shaft. The material of the polymeric wrapping is designed to shrink when exposed to the heat of the oven in which the wrapped inner mandrel is cured, providing compressive stress which forces air and gases out of the composite while curing. After the shaft is removed from the oven, the inner mandrel is removed, and the exterior of the composite shaft can be machined or ground to the desired outer dimensions and appearance.

[0005] Composite shafts manufactured using these methods are generally strong, in order to minimize the shafts bending, breaking, or splintering upon impacting a target. Additionally, such composite shafts are lightweight, allowing the arrow or crossbow bolt to fly faster and retain more kinetic energy during flight.

[0006] We have discovered that there exists a need for a composite arrow or crossbow bolt shaft with a constant outer diameter but varying thickness, which allows the bolt shaft's center of mass to be varied arrow or crossbow, as well as a need for manufacturing techniques for such shafts. We have also discovered that there exists a need for improvements to the structural integrity of known shafts, as well as improvements of the vibration damping properties of known shafts to retain more kinetic energy during flight. We have further discovered that such improvements can be made through the use of various combinations in the selection of material components and manufacturing processes for such shafts.

SUMMARY OF EMBODIMENTS OF THE INVENTION

[0007] Embodiments of the invention are directed to an arrow or crossbow bolt shaft that includes a shaft inner diameter that varies along a length of the shaft, a shaft outer diameter of that remains constant along the length of the shaft, and a hollow core including an outer diameter that varies along the length of the shaft. By varying the inner diameter of the shaft along the length of the shaft, the location of shaft's center of mass can be varied in a manner that can affect the shaft's aerodynamic properties, in-flight capabilities, and strength. Additionally, controlling the inner profile of the arrow or crossbow bolt shaft allows for control of the stiffness and strength characteristics of the shaft assembly.

[0008] In certain embodiments, the shaft inner diameter and hollow core outer diameter vary along the entire length of the shaft.

[0009] In certain embodiments, the hollow core outer diameter and the shaft inner diameter vary continuously along the length of the shaft. In other embodiments, the shaft is a stepped shaft including a plurality of portions, and each of the plurality of portions has a constant shaft inner diameter that is different than a shaft inner diameter of each of the other portions.

[0010] In certain embodiments, a stepped shaft includes at least three portions. In certain embodiments, each of the plurality of portions of the stepped shaft has the same length. In other embodiments, at least one of the plurality of portions of the stepped shaft has a different length than another of the plurality of portions of the stepped shaft.

[0011] In certain embodiments, a stepped shaft includes a tapered portion, in which the shaft inner diameter and hollow core outer diameter vary continuously along the length of the tapered portion.

[0012] In certain embodiments, the center of mass of the shaft is closer to a tip portion of the shaft than to a tail portion of the shaft. In certain further embodiments, the center of mass of the shaft is between approximately 10% and approximately 20% front of center. In still further embodiments, the center of mass of the shaft is approximately 13% front of center.

[0013] The shaft includes fibers of one or more materials. The materials may be carbon fibers, stainless steel fibers, spring steel fibers, steel fibers, titanium fibers, magnesium fibers, aluminum fibers, linearized polyethylene or spectra fibers, silicon carbide fibers, cellulose fibers, or fiberglass fibers. The carbon fibers may be high modulus carbon fibers or intermediate modulus carbon fibers.

[0014] Embodiments of the shaft include thermoset resin or thermoplastic resin. The thermoset resin can be an epoxy, polyester, vinylester, phenolic, or urethane. The thermoplastic resin can be polyether ether ketone (PEEK), polymethyl methacrylate (PMMA), acrylic, nylon, or polyethylene.

[0015] Embodiments of the invention are directed to methods of manufacturing arrow or crossbow bolt shafts, including shaping an inner mandrel to have an outer diameter that varies along the length of the inner mandrel, wrapping the inner mandrel with wrapping material, heating the inner mandrel and the wrapping material to form a shaft around the inner mandrel, removing the inner mandrel from the interior of the shaft, and mechanically processing the shaft to shape the shaft to its desired final dimensions.

[0016] In certain embodiments, shaping the inner mandrel includes turning the inner mandrel on a lathe.

[0017] The wrapping material includes fibers of one or more materials. The materials may be carbon fibers, stainless steel fibers, spring steel fibers, steel fibers, titanium fibers, magnesium fibers, aluminum fibers, linearized polyethylene or spectra fibers, silicon carbide fibers, cellulose fibers, or fiberglass fibers. The carbon fibers may be high modulus carbon fibers or intermediate modulus carbon fibers.

[0018] In certain embodiments, the wrapping material includes a dry carbon fiber mat that has been coated with liquid thermoset resin, and wrapping the inner mandrel with wrapping material includes manually wrapping the coated carbon fiber mat around the inner mandrel. In further embodiments, heating the inner mandrel and the wrapping material includes placing the inner mandrel and coated carbon fiber mat in a press and molding the coated carbon fiber mat at an elevated temperature.

[0019] In certain embodiments, the wrapping material is a thermoplastic, pre-impregnated carbon fiber tape and either a polypropylene or nylon tape, and wrapping the inner mandrel with wrapping material includes wrapping the pre-impregnated carbon fiber tape around the inner mandrel and then wrapping the polypropylene or nylon tape around the carbon fiber tape. In further embodiments, heating the inner mandrel and the wrapping material includes placing the inner mandrel wrapped with the tapes into an oven and curing the tapes at an elevated temperature.

[0020] In certain embodiments, the wrapping material include a self-adhesive, pre-impregnated carbon fiber fabric, and wrapping the inner mandrel with wrapping material includes wrapping the fabric around the inner mandrel.

[0021] In certain embodiments, mechanically processing the shaft includes sanding or grinding the shaft to its desired final dimensions. In further embodiments, sanding or grinding the shaft to its desired final dimensions includes sanding or grinding the shaft until the shaft has a constant outer diameter along the entire length of the shaft. In further embodiments, the shaft, having its desired final dimensions, is coated with a thin polymeric tube or fabric to reduce the friction on the exterior of the shaft. In still further embodiments, the thin polymeric tube or fabric includes polypropylene, polyethylene, vinyl, or nylon.

[0022] In certain embodiments, the inner mandrel includes steel, aluminum, or titanium.

[0023] Embodiments of the present invention are directed to methods of manufacturing arrow or crossbow bolt shafts. The methods include shaping an inner mandrel so that the outer diameter of the inner mandrel varies along the length of the inner mandrel, tri-axially braiding fibers of one or more materials around the inner mandrel, heating the inner mandrel and the tri-axially braided fibers to form a shaft around the inner mandrel, and removing the inner mandrel from the interior of the shaft. The fibers of one or more materials may be carbon fibers, stainless steel fibers, spring steel fibers, steel fibers, titanium fibers, magnesium fibers, aluminum fibers, linearized polyethylene or spectra fibers, silicon carbide fibers, cellulose fibers, or fiberglass fibers. The carbon fibers may be high modulus carbon fibers or intermediate modulus carbon fibers.

[0024] In certain embodiments, tri-axially braiding fibers of one or more materials around the inner mandrel includes varying the speed at which the inner mandrel moves longitudinally during the tri-axial braiding of the fibers around the inner mandrel.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] FIG. **1**A is a side view of a composite shaft design with a tapered inner diameter and a constant outer diameter.

[0026] FIG. **1**B is a cross-sectional view of a portion of the shaft design of FIG. **1**A.

[0027] FIG. **2**A is a side view of a composite shaft design with a stepped inner diameter and a constant outer diameter.

[0028] FIG. **2**B is a cross-sectional view of a portion of the composite shaft design of FIG. **2**A.

[0029] FIG. **3**A is a perspective view of an inner mandrel used in a manufacturing process for a composite shaft.

[0030] FIG. **3**B is a perspective view of the inner mandrel of FIG. **3**A being wrapped with a composite material during the manufacturing process for a composite shaft.

[0031] FIG. **4** is a side view depicting tri-axial braiding of fibers around a tapered inner mandrel.

[0032] FIG. **5** is a top view depicting the movement of the bobbins tri-axially braiding fibers around the tapered inner mandrel of FIG. **4**.

[0033] FIG. **6** depicts the interwoven tri-axially braided fibers resulting from the process depicted in FIGS. **4** and **5**.

DETAILED DESCRIPTION OF THE INVENTION

[0034] The present invention is directed to arrow and crossbow bolt shafts and methods for manufacturing such shafts. For the purposes of the present invention, both arrow shafts and crossbow bolt shafts will be referred to collectively as "shafts."

[0035] FIGS. **1**A and **1**B illustrate an embodiment **100** of a composite shaft **105** having a hollow core **110**. The shaft **105** has a constant outer diameter surrounding the hollow core **110**, but the thickness (and the inner diameter) of the shaft **105** gradually varies along the length of the shaft **105**. Specifically, the thickness of the shaft **105** is greater (and the inner diameter of the shaft smaller) at the tip end **105***a* than it is at the tail end **105***b*. Correspondingly, the outer diameter of the hollow core is greater at the tail end **110***b* than it is at the tip end **105***a*, as the shaft **105** decreases in thickness. In this embodiment **100**, the thickness of the composite shaft **105** gradually and steadily decreases from the tip end **105***a* to the tail end **105***b* (for the purposes of the present invention, a so-called "tapered" shaft design), even as the outer diameter of the composite shaft **105** remains constant.

[0036] In the embodiment **100** depicted in FIGS. **1**A and **1**B, the greater thickness of the composite shaft **105** at the tip end **105***a* than at the tail end **105***b* results in the shaft **105** having a center of mass that is closer to the tip end **105***a* than to the tail end **105***b*.

[0037] A shaft with a center of mass closer to the tip end than the tail end is referred to as a shaft that is "front of center." The percentage to which a shaft is "front of center" is equal to the percent difference between the physical midpoint, of the shaft (by length) and the center of gravity of the shaft, as compared to the total length of the shaft. The front of center percentage value can be calculated using the following equation, where "L" represents the total length of the shaft, and "B" represents the distance from the tail end of the shaft to the center of mass of the shaft:

$$\text{Front of Center }\% = \left(\frac{B}{L} - 0.5\right) * 100\%$$

[0038] In some embodiments, the center of mass of the shaft **105** may be between about 5% and about 20% front of center, or between about 10% and 15% front of center. In certain embodiments, the center of mass of the shaft **105** is about 13% front of center.

[0039] As the center of mass moves closer to the tip end of the shaft (i.e., as the percent front of center of the shaft increases), the shaft **105** will have better stability during flight, as the increased distance between the fletchings on the tail of the shaft **105** and the center of gravity of the shaft **105** allow the fletchings to more effectively stabilize the shaft **105** in flight, straightening the shaft **105** by rotating the shaft **105** around its center of pressure. However, as the percentage front of center value of the shaft **105** increases, the shaft **105** will dive more quickly due to the greater weight distribution in the nose end **105***a* of the shaft **105**, limiting the distance that the shaft **105** can fly. In contrast, a shaft **105** with a lower percentage front of center value will be less stable during flight, but will hold its trajectory better and fly longer distances.

[0040] FIGS. **2**A and **2**B illustrate another embodiment **200** of a composite shaft **205** having a hollow core **210**. In this embodiment **200**, like the embodiment **100** depicted in FIGS. **1**A and **1**B, the shaft **205** also has a constant outer diameter. However, instead of gradually tapering in thickness like the embodiment **100** depicted in FIGS. **1**A and **1**B, the shaft **205** of embodiment **200** includes three distinct portions **205***a*, **205***b*, and **205***c*. In each one of the portions **205***a*, **205***b*, and **205***c*, the shaft **205** has a thickness that is constant, but different than the thickness of each of the other portions. For the purposes of the present invention, such a design **200** is known as a "stepped" shaft.

[0041] The shaft **205** is thickest in the portion **205***a* nearest the tip of the shaft **205**, less thick in the middle portion **205***b*, and the least thick in the portion **205***c* nearest to the tail end of the shaft **205**. Correspondingly, the hollow core **210** of the shaft has its largest outer diameter in the tail portion **210***c*, a smaller outer diameter in middle portion **210***b*, and an even smaller outer diameter in nose portion **210***a*. Like the embodiment **100** depicted in FIGS. **1**A and **1**B, the stepped shaft embodiment **200** has a center of gravity that is front of center.

[0042] In embodiment **200** displayed in FIGS. **2**A and **2**B, the stepped shaft **205** has three portions **205***a*, **205***b*, and **205***c*. However, in other embodiments, a stepped shaft may have two, three, four, or another number of distinct stepped portions. Furthermore, in some embodiments, the length of each portion may be equal to the length of each of the other portions of the stepped shaft, while in other embodiments, each portion of the stepped shaft may have a different length. For example, in one embodiment, a stepped shaft composed of three portions may have first and second portions having the same length, with the third portion having a different length than those first and second portions. In another embodiment, however, the third portion will have the same length as the first and second portions of that stepped shaft. By "tuning" the number of stepped portions in the shaft, as well as the relative length of these stepped portions of the shaft, a manufacturer of such shafts can adjust the vibration frequency of the shaft design.

[0043] In some embodiments, some portions of the shaft are stepped, while other portions of the same shaft are tapered. For example, in one embodiment, a shaft has three portions, where the first and third portions are stepped portions, each of these stepped portions of the shaft having a constant thickness different than the other stepped portion of the shaft (but identical outer diameters). However, in a second portion of the shaft located between the stepped first and third portions, the thickness of the shaft tapers gradually and continuously down from a higher thickness in the first portion of the shaft to a lower thickness in the third portion of the shaft.

[0044] In embodiments **100** and **200** of the invention depicted in FIGS. **1**A-**1**B and **2**A-**2**B, the shafts **105** and **205** include one or more types of fibers. In these embodiments, the different types of material fibers used to construct the shafts **105** and **205** may be non-metallic or metallic fibers, including carbon fibers, titanium fibers, stainless steel fibers, spring steel fibers, steel fibers, aluminum fibers, cellulose fibers, fiberglass fibers, silicon carbide fibers, magnesium fibers, and linearized polyethylene or spectra.

[0045] To obtain an arrow or crossbow bolt shaft having a desired selection of material and mechanical properties, a designer may select desired material types and relative quantities of fibers from which to manufacture a shaft. High-modulus carbon fibers (having a modulus of about 400 gPa) can be used to construct a shaft having relatively high stiffness and strength, few defects, and small carbon fibers. Using intermediate-modulus carbon fibers (having a modulus of about 285 gPa), on the other hand, will result in a shaft that has relatively lower stiffness and/or strength in comparison to a shaft made of high-modulus carbon fibers, but that increases the margin for error in an archer's accuracy. For example, the lower stiffness of an intermediate-modulus carbon fiber shaft aids in negating the effects of the so-called "archer's paradox" (the name given to the phenomenon in which an arrow travels straight at a target at which a bow is pointed, even though the arrow shaft must be pointed to the side of the target as it rests against the bow)—a property known as the "dynamic spine" of the shaft.

[0046] Metallic fibers, such as titanium or magnesium fibers, impart different properties to a composite shaft. For example, titanium or magnesium fibers can be hexagonally close-packed together because of the orientation of the titanium or magnesium atoms within the metal lattice. Such metallic fibers aid with vibration damping upon release, resulting in a reduced loss of kinetic energy during flight from wobbling/vibration of the arrow or crossbow bolt. This reduced in-flight loss of kinetic energy, due to the vibration damping properties of the metallic fibers, ensures that the shaft strikes its target with greater velocity and energy, resulting in increased penetrating power and effectiveness. Furthermore, metallic fibers, such as titanium and steel, have relatively high toughness, causing the metal fibers of the composite shaft to absorb energy upon impact and reducing the probability that the shaft will fracture or break.

[0047] To obtain a shaft having the desired combination of stiffness, strength, toughness, vibration damping, and other properties, a mix of carbon fibers and metallic fibers can be used to construct composite shaft embodiments of the present invention. Different material types and changes in the relative amounts of the different fiber materials may be used to adjust the desired characteristics of a composite shaft. In one embodiment of the invention, for example, a composite shaft may be manufactured from 20% vibration-damping fibers (such as titanium and/or magnesium fibers), which decrease vibration and wobbling and provide toughness to the shaft, and 80% carbon fibers, which give the shaft stiffness and strength.

[0048] The composite shafts of the present invention are manufactured by forming the shafts around an inner mandrel, which is then removed from the interior of the shaft, leaving behind the hollow composite arrow or crossbow bolt shaft. In various embodiments, the inner mandrel may be made from, for example, aluminum, steel, or titanium. FIG. **3**A illustrates an exemplary inner mandrel **300**. The outer diameter of inner mandrel **300** varies in size along the length of inner mandrel **300**, and the tapered profile of inner mandrel **300** corresponds to the outer diameter of the hollow inner core of a composite shaft that is formed around inner mandrel **300**. The inner mandrel **300** can be shaped by turning the inner mandrel **300** on a lathe so that its outer diameter has the desired profile for the hollow inner core of a composite shaft to be manufactured around the inner mandrel **300**. The inner mandrel **300** can be a tapered mandrel, a stepped mandrel, or a combination of the two.

[0049] Various manufacturing processes can be utilized to manufacture the composite shafts of the present invention. In a first set of embodiments of the manufacturing processes, after an inner mandrel **300** has been shaped to the desired profile, one or more composite materials are wrapped around the inner mandrel **300**. This process is depicted in FIG. **3**B, in which composite tape **310** is being wrapped around inner mandrel **300**, with inner mandrel **300** being tightly gripped in place by a machine during wrapping of the tape **310**. The wrapping of tape **310** is typically an automated process performed by a machine. The machine for wrapping tape **310** may be a center-less tape wrapping machine or a "lathe" type wrapping machine.

[0050] By altering the angle at which the tape **310** wraps around inner mandrel **300**, a designer may control the strength and other mechanical properties of the composite shaft that is manufactured around inner mandrel **300**. The two main forces acting on such shafts are: 1) tensional/compressional forces, which act longitudinally along the main axis of a shaft, and which are caused, for example, by a shaft striking a target head on; and 2) buckling forces, which act radially outward from the longitudinal axis of an shaft, and which result from the shaft striking a target at an angle (and not directly head-on).

[0051] Wrapping the tape **310** more radially around inner mandrel **300** causes the resulting composite shaft to have more radial support, allowing the shaft to better resist the buckling forces described above. In some embodiments, therefore, the tape **310** is wrapped at a more radial angle at the tip portion of the shaft, giving more radial support to the shaft at the point nearest to where the shaft strikes a target and helping that portion of the shaft resist the buckling forces generated when the shaft strikes a target at an angle. In areas of the shaft further from the tip end of the shaft, the tape **310** may be wrapped at a more longitudinal angle around inner mandrel **300**, causing the shaft to have more longitudinal support in those areas and be better able to resist the tensional/compressional forces generated along the main axis of the shaft.

[0052] To further vary the capabilities and properties of the shaft, additional tape **310** may be laid along the length of the inner mandrel **300** to provide additional axial stiffness, or wrapped radially around desired portions of the inner mandrel **300** to provide additional radial support. Two or more different tapes **310**, each made of fibers of different materials and/or different fiber sizes can also be used in a single composite shaft, so that the resulting shaft has the combination of properties desired by a designer.

[0053] In some embodiments, the composite tape **310** is pre-impregnated ("pre-preg") composite tape which is impregnated with a thermoplastic. The thermoplastic may be a resin, and the thermoplastic resin may be made of polyether ether ketone (PEEK), polymethyl methacrylate (PMMA), acrylic, nylon, and/or polyethylene.

[0054] In some embodiments of the pre-preg tape manufacturing process, after the pre-preg tape **310** has been wrapped around inner mandrel **300**, a polypropylene or nylon tape is then wrapped around the pre-preg composite tape **310**. Inner mandrel **300** and the layers of tape **310** wrapped around it are then placed in an oven, and cured at an appropriate temperature for the particular thermoplastic resin used in the pre-preg tape **310**. As inner mandrel **300** and the wrapped layers of tape **310** bake in the oven, the polypropylene or nylon tape shrinks, applying compressive force to the pre-preg tape **310** and inner mandrel **300** and forcing air out of the entire pre-preg tape **310** and inner mandrel **300** assembly, resulting in a composite shaft having a varying inner profile being formed around inner mandrel **300**.

[0055] In some other embodiments of the pre-preg tape manufacturing process, instead of wrapping the pre-preg tape **310** and inner mandrel **300** with nylon or polypropylene tape, the pre-preg tape **310** and inner mandrel **300** can be placed in an autoclave. The pressure and temperature are then elevated within the autoclave, curing the pre-preg tape **310** and forcing air out of the entire pre-preg tape **310** and inner mandrel **300** assembly, resulting in a composite shaft having a varying inner profile being formed around inner mandrel **300**.

[0056] In a second type of embodiments of the manufacturing process, inner mandrel **300** is manually wrapped with a dry composite fiber mat that is then coated with liquid thermoset resin—a process known as a "wet layup" process. The liquid thermoset resin can be an epoxy, polyester, vinylester, phenolic, and/or urethane thermoset resin. The thermoset resin is forced to infiltrate the fabric of the composite fiber mat wrapped around the inner mandrel **300**, and then the wrapped inner mandrel is placed into a press and molded at an elevated temperature to create a composite shaft around inner mandrel **300**. In some embodiments, the elevated temperature at which the wrapped, soaked fabric is molded is approximately 200 degrees Fahrenheit.

[0057] In a third type of embodiments of the manufacturing process, the composite shaft can be manufactured around inner mandrel **300** using a process known as "roll wrapping." In the roll wrapping process, a woven composite fabric that is pre-impregnated with a thermoplastic resin, such as polyether ether ketone (PEEK), polymethyl methacrylate (PMMA), acrylic, nylon, or polyethylene, is wrapped around inner mandrel **300** by rolling inner mandrel **300** between two plates. The pre-impregnated woven composite fabric is self-adhesive, causing the pre-preg woven composite fabric to adhere to inner mandrel **300** for further processing. The pre-preg woven fabric adhered to inner mandrel **300** can then be wrapped with nylon or polypropylene tape and cured, as described above, or can be cured in an autoclave, also as described above.

[0058] Whether the composite shaft is manufactured using the pre-preg tape, wet layup, or roll wrapping methods described above, after curing the composite shaft, inner mandrel **300** is removed from the interior of the shaft, leaving a composite tube having a profiled hollow interior (whether tapered, stepped, or a combination of the two). The exterior of the composite shaft can then be sanded, ground, or otherwise machined so that the composite shaft has the final exterior dimensions desired by the manufacturer—for example, a constant outer diameter along the length of the composite shaft.

[0059] After the composite shaft has been sanded or ground to the desired final exterior dimensions, in some embodiments, the composite shaft is coated with a thin polymeric tube or fabric to reduce the coefficient of friction on the exterior surface of the composite shaft. In some embodiments, the polymeric tube or fabric includes polypropylene, polyethylene, vinyl, or nylon.

[0060] In addition to the various wrapping, curing, and sanding/grinding manufacturing processes described above, in other embodiments of the present invention, the composite shaft is manufactured using a triaxial braiding process.

[0061] FIGS. **4** and **5** depict an embodiment of a triaxial braiding manufacturing process to assemble a composite shaft **400** made up of triaxially braided fibers **425**, **435**, and **445**. Fibers **425**, **435**, and **445** are braided around a profiled inner mandrel **410**, which moves in direction **450** along the longitudinal axis of inner mandrel **410** through the triaxial braiding apparatus. Inner mandrel **410** can be a tapered mandrel, a stepped mandrel, or a combination of the two.

[0062] As illustrated by the embodiment of the manufacturing process depicted in FIG. **4**, threads **425** are unspooled off of bobbins **420***a* and **420***b* and braided at a first angle to the longitudinal axis of inner mandrel **410**, threads **435** are unspooled off of bobbins **430***a* and **430***b* and braided at a second angle to the longitudinal axis of inner mandrel **410**, and threads **445** are unspooled off of longitudinal thread guides **440***a* and **440***b* parallel to the longitudinal axis of inner mandrel **410**. While the exemplary illustration of FIG. **4** depicts only two bobbins **420***a* and **420***b* unspooling threads **425**, two bobbins **430***a* and **430***b* unspooling threads **435**, and two longitudinal thread guides **440***a* and **440***b*, a triaxial braiding assembly for manufacturing composite arrow or crossbow bolt shafts will have a greater number of bobbins **420***a-b* and **430***a-b* and longitudinal thread guides **440***a* and **440***b* surrounding inner mandrel **410**, and a correspondingly greater number of threads **425**, **435**, and **445** being triaxially braided onto inner mandrel **410**. The particular number of bobbins and longitudinal thread guides utilized in the triaxial braiding manufacturing process depends on the size of inner mandrel **410** upon which the threads are being braided.

[0063] As inner mandrel **410** moves along its longitudinal axis **450** through the triaxial braiding plane **460**, threads **425**, **435**, and **445** are unspooled from bobbins **420***a-b* and **430***a-b* and longitudinal thread guides **440***a* and **440***b* and converge together into a braid within zone **470**. And as inner mandrel **410** moves along its longitudinal axis **410** through the triaxial braiding plane **460**, bobbins **420***a-b* and **430***a-b* rotate around inner mandrel **410** on the triaxial braiding plane **460** in a spiraling pattern, as depicted by FIG. **5**. FIG. **5** is a top-down view of inner mandrel **410** in the triaxial braiding apparatus, illustrating bobbin **420** moving along spiraling path **428** around inner mandrel **410** on triaxial braiding plane **460** to braid thread **425** onto inner mandrel **410**, and bobbin **430** moving along spiraling path **438** in the opposing direction around inner mandrel **410** on triaxial braiding plane **460** to braid thread **435** onto inner mandrel **410**.

[0064] While the exemplary illustration in FIG. **5** only depicts two bobbins **420** and **430** discussed above, a triaxial braiding assembly for manufacturing composite arrow or crossbow bolt shafts will have a greater number of bobbins **420** and **430** surrounding inner mandrel **410** and moving along paths **428** and **438**, with the particular number of bobbins depending on the size of inner mandrel **410**.

[0065] By varying the speed at which inner mandrel **410** moves along its longitudinal axis **450** through the triaxial braiding plane **460** in comparison to the speed at which bobbins **420** and **430** rotate around inner mandrel **410** on the triaxial braiding plane **460** along paths **428** and **438**, a manufacturer of composite shaft **400** can adjust the angle of the threads **425** and **435** in the composite shaft **400** in comparison to the longitudinally oriented threads **445**. By slowing the relative speed of the longitudinal movement **450** of inner mandrel **410**, threads **425** and **445** will be relatively more radially oriented, providing more radial support for composite shaft **400** to resist buckling forces caused by the shaft **400** striking a target off-center. Conversely, by increasing the relative speed of the longitudinal movement **450** of inner mandrel **410**, threads **425** and **445** will be relatively more longitudinally oriented, providing more axial support for composite shaft **400** to resist tensional/compressional forces along the longitudinal axis of the composite shaft **400**.

[0066] FIG. **6** illustrates an exemplary embodiment of a triaxial braiding pattern of fibers **425**, **435**, and **445**, resulting from the triaxial braiding process depicted in FIGS. **4** and **5**. While fibers **425** and **435** are depicted in FIG. **6** as being interwoven at a consistent 45 degree angle in comparison to longitudinal fibers **445**, as discussed above, fibers **425** and **435** may be braided at varying angles to longitudinal fibers **445** at different points in the composite shaft **400**. For example, the fibers **425** and **435** may be more radially oriented (to provide more support against buckling forces) at the tip portion of the shaft **400**, but more longitudinally oriented at the tail portion of the shaft **400**.

[0067] In addition to varying the angles of fibers **425** and **435** as discussed above, fibers **425**, **435**, and **445** may include fibers of one or more different materials. For example, fibers **425**, **435**, and **445** may include high-modulus or intermediate-modulus carbon fibers, titanium fibers, stainless steel fibers, spring steel fibers, steel fibers, aluminum fibers, cellulose fibers, fiberglass fibers, silicon carbide fibers, magnesium fibers, and linearized polyethylene or spectra. In one exemplary embodiment, fibers **425**, **435**, and **445** are made of 20% vibration-damping fibers (such as metallic titanium and/or magnesium fibers), which decrease vibration and wobbling and provide toughness to the shaft **400**, and 80% carbon fibers, which give the shaft **400** stiffness and strength. Fibers **425**, **435**, and **445** may also vary in their thickness, which also affects the strength, stiffness, and other properties of the composite shaft **400**.

[0068] After the tri-axial braiding process is completed to form a braided pattern, as shown in FIG. **6**, the composite shaft **400** is cured. In some embodiments, fibers **425**, **435**, and **445** are pre-impregnated with a thermoplastic resin, such as polyether ether ketone (PEEK), polymethyl methacrylate (PMMA), acrylic, nylon, or polyethylene. In these embodiments, the pre-impregnated fibers **425**, **435**, and **445** of composite shaft **400** can be wrapped in polypropylene or nylon tape and then cured in an oven, or the pre-preg fibers **425**, **435**, and **445** can be cured in an autoclave under elevated temperature and pressure.

[0069] In other embodiments, in which the fibers **425**, **435**, and **445** are not pre-impregnated with a thermoplastic, the fibers **425**, **435**, and **445** of the composite shaft **400** can be coated with liquid thermoset resin in a wet layup process. The thermoset resin may be epoxy, polyester, vinylester, phenolic, or urethane. After the thermoset resin infiltrates fibers **425**, **435**, and **445**, the tri-axially braided fibers **425**, **435**, and **445** and the profiled inner mandrel **410** are placed into a press and molded at an elevated temperature to create a composite shaft **400** around inner mandrel **410**. In some exemplary embodiments, the elevated temperature at which the wrapped, soaked braided fibers **425**, **435**, and **445** are molded is approximately 200 degrees Fahrenheit.

[0070] After the fibers **425**, **435**, and **445** of the composite shaft **400** are cured, inner mandrel **410** is removed from the interior of composite shaft **400**, leaving a hollow, profiled interior in the composite shaft **400**, the hollow core of composite shaft **400** having an outer diameter that corresponds to the outer diameter of the profiled inner mandrel **410**. The triaxial braiding manufacturing method allows the fibers **425**, **435**, and **445** to be woven around inner mandrel **410** to form a composite shaft **400** having a constant, uniform outer diameter, reducing the need to sand or grind the composite shaft **400** after the curing process has completed, and avoiding material waste. In some embodiments, the composite shaft **400** is then coated with a thin polymeric tube or fabric to reduce the coefficient of friction on the exterior surface of the composite shaft **400**. In some embodiments, the polymeric tube or fabric includes polypropylene, polyethylene, vinyl, or nylon.

We claim:

1. An arrow or crossbow bolt shaft comprising:

a shaft inner diameter that varies along a length of the shaft;

a shaft outer diameter that remains constant along the length of the shaft; and

a hollow core comprising an outer diameter that varies along the length of the shaft.

2. The shaft of claim **1**, wherein the shaft inner diameter and hollow core outer diameter vary along the entire length of the shaft.

3. The shaft of claim **1**, wherein the hollow core outer diameter and the shaft inner diameter vary continuously along the length of the shaft.

4. The shaft of claim **1**, wherein:

the shaft is a stepped shaft comprising a plurality of portions; and

each of the plurality of portions has a constant shaft inner diameter that is different than a shaft inner diameter of each of the other portions.

5. The shaft of claim **4**, wherein the stepped shaft comprises at least three portions.

6. The shaft of claim **4**, wherein each of the plurality of portions of the stepped shaft has the same length.

7. The shaft of claim **4**, wherein at least one of the plurality of portions of the stepped shaft has a different length than another of the plurality of portions.

8. The shaft of claim **4**, wherein the stepped shaft comprises a tapered portion, in which the shaft inner diameter and hollow core outer diameter vary continuously along the length of the tapered portion.

9. The shaft of claim **1**, wherein the center of mass of the shaft is closer to a tip portion of the shaft than to a tail portion of the shaft.

10. The shaft of claim **9**, wherein the center of mass of the shaft is between approximately 10% and approximately 20% front of center.

11. The shaft of claim **1**, wherein the shaft comprises fibers of one or more materials.

12. The shaft of claim **11**, wherein the fibers of one or more materials comprise carbon fibers, stainless steel fibers, spring steel fibers, steel fibers, titanium fibers, magnesium fibers, aluminum fibers, linearized polyethylene or spectra fibers, silicon carbide fibers, cellulose fibers, or fiberglass fibers.

13. The shaft of claim **1**, wherein the shaft comprises thermoset resin or thermoplastic resin.

14. The shaft of claim **13**, wherein the thermoset resin comprises epoxy, polyester, vinylester, phenolic, or urethane.

15. The shaft of claim **13**, wherein the thermoplastic resin comprises polyether ether ketone (PEEK), polymethyl methacrylate (PMMA), acrylic, nylon, or polyethylene.

16. A method of manufacturing an arrow or crossbow bolt shaft, comprising:

shaping an inner mandrel so that an outer diameter of the inner mandrel varies along the length of the inner mandrel;

wrapping the inner mandrel with wrapping material;

heating the inner mandrel and the wrapping material to form a shaft around the inner mandrel;

removing the inner mandrel from the interior of the shaft; and

mechanically processing the shaft to shape the shaft to its desired final dimensions.

17. The method of claim **16**, wherein shaping the inner mandrel comprises turning the inner mandrel on a lathe.

18. The method of claim **16**, wherein the wrapping material comprises fibers of one or more materials.

19. The method of claim **18**, wherein the fibers of one or more materials comprise carbon fibers, stainless steel fibers, spring steel fibers, steel fibers, titanium fibers, magnesium fibers, aluminum fibers, linearized polyethylene or spectra fibers, silicon carbide fibers, cellulose fibers, or fiberglass fibers.

20. The method of claim **19**, wherein the wrapping material comprises thermoset resin or thermoplastic resin.

21. The method of claim **20**, wherein:

the wrapping material comprises a dry carbon fiber mat that has been coated with liquid thermoset resin; and

wrapping the inner mandrel with wrapping material comprises manually wrapping the coated carbon fiber mat around the inner mandrel.

22. The method of claim **21**, wherein heating the inner mandrel and the wrapping material comprises placing the inner mandrel and the coated carbon fiber mat in a press and molding the coated carbon fiber mat at an elevated temperature.

23. The method of claim **20**, wherein:

the wrapping material comprises a thermoplastic, pre-impregnated carbon fiber tape and one of a polypropylene type or a nylon tape; and

wrapping the inner mandrel with wrapping material comprises wrapping the pre-impregnated carbon fiber tape around the inner mandrel and then wrapping the polypropylene tape or the nylon tape around the carbon fiber tape.

24. The method of claim **23**, wherein heating the inner mandrel and the wrapping material comprises placing the inner mandrel wrapped with the tapes into an oven and curing the tapes at an elevated temperature.

25. The method of claim **19**, wherein:

the wrapping material comprises a self-adhesive, pre-impregnated carbon fiber fabric; and

wrapping the inner mandrel with the wrapping material comprises wrapping the fabric around the inner mandrel.

26. The method of claim **16**, wherein mechanically processing the shaft comprises sanding or grinding the shaft to its desired final dimensions.

27. The method of claim **26**, wherein sanding or grinding the shaft to its desired final dimensions comprises sanding or grinding the shaft until the shaft has a constant outer diameter along the entire length of the shaft.

28. The method of claim **27**, further comprising coating the shaft having its desired final dimensions with a thin polymeric tube or fabric to reduce the friction on the exterior of the shaft.

29. The method of claim **28**, wherein the thin polymeric tube or fabric comprises polypropylene, polyethylene, vinyl, or nylon.

30. The method of claim **16**, wherein the inner mandrel comprises steel, aluminum, or titanium.

31. A method of manufacturing an arrow or crossbow bolt shaft, comprising:

shaping an inner mandrel so that the outer diameter of the inner mandrel varies along a length of the inner mandrel;

tri-axially braiding fibers of one or more materials around the inner mandrel;

heating the inner mandrel and the tri-axially braided fibers to form a shaft around the inner mandrel; and

removing the inner mandrel from the interior of the shaft.

32. The method of claim **31**, wherein the fibers of one or more materials comprise carbon fibers, titanium fibers, stainless steel fibers, spring steel fibers, steel fibers, aluminum fibers, cellulose fibers, fiberglass fibers, silicon carbide fibers, or magnesium fibers.

33. The method of claim **32**, wherein the carbon fibers are high-modulus carbon fibers or intermediate-modulus carbon fibers.

34. The method of claim **31**, wherein tri-axially braiding fibers of one or more materials around the inner mandrel comprises varying a speed at which the inner mandrel moves longitudinally during the tri-axial braiding of the fibers around the inner mandrel.

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