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(54) **ENHANCED METAL-METAL-MATRIX COMPOSITE WEAPON BARRELS AND WAYS OF MAKING THE SAME**

(52) **U.S. Cl.**
CPC *F41A 21/02* (2013.01); *F41A 13/00* (2013.01); *F41A 21/24* (2013.01)

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(57) **ABSTRACT**

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Weapon barrels are disclosed which offer improved thermal performance and rigidity with no, minimal or negative weight increase. In general the barrel comprises a barrel core surrounded by a lightweight, thermally conductive sleeve made from metal-matrix composite (MMC) materials, also referred to as metal-matrix material. The increased diameter of the sleeve improves the barrel's stiffness and the sleeve's thermal conductivity and distributes the heat more evenly along the barrel. Manufacturing and joining techniques are disclosed as well as materials and material combinations that allow the barrel to perform at high cadence over the whole temperature range the barrel is used. Hot spots may be reduced and more surface area can contribute to heat dissipation. The increased diameter also allows integration of phase changing and/or vibration dampening materials, which further enhance performance.

(21) Appl. No.: **15/456,374**

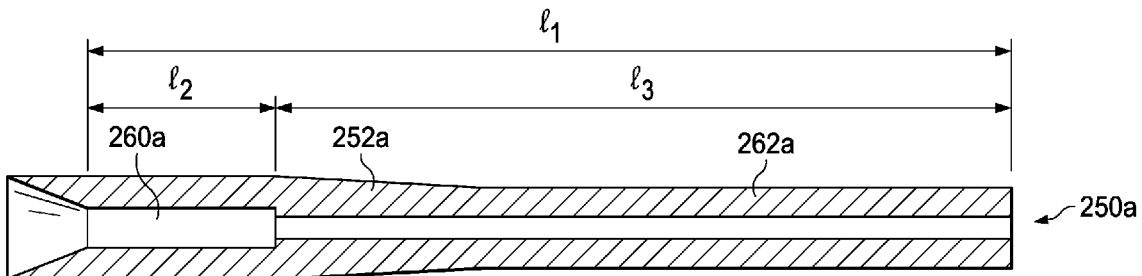
(22) Filed: **Mar. 10, 2017**

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(60) Provisional application No. 62/306,375, filed on Mar. 10, 2016.

Publication Classification

(51) **Int. Cl.**
F41A 21/02 (2006.01)
F41A 21/24 (2006.01)
F41A 13/00 (2006.01)



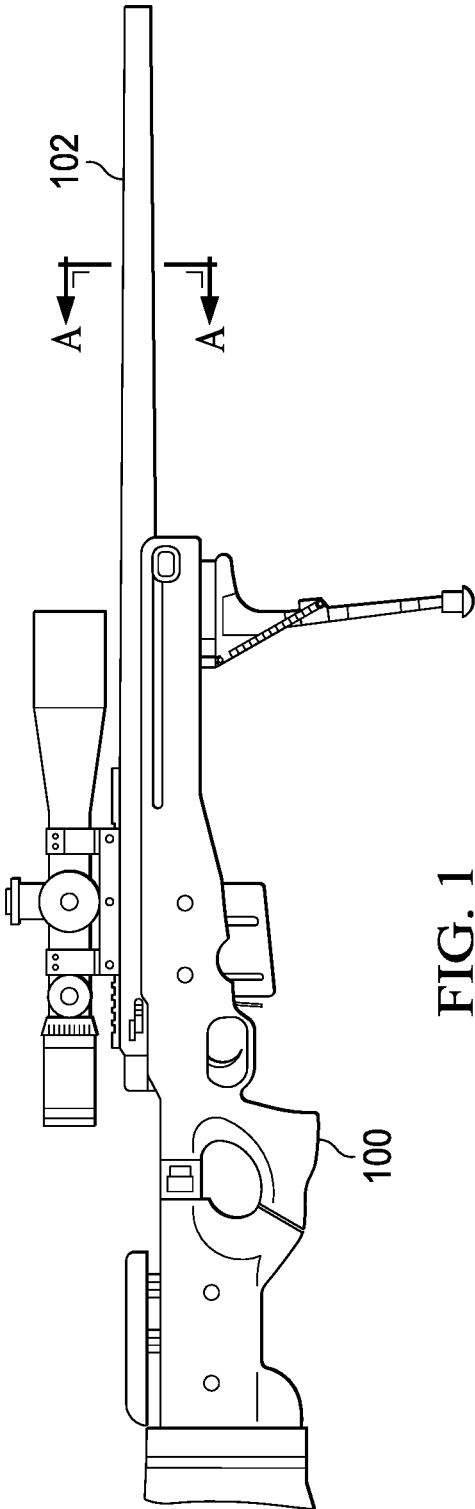


FIG. 1

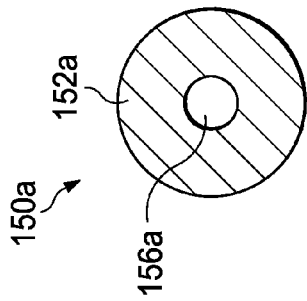


FIG. 2A

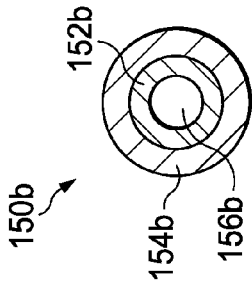


FIG. 2B

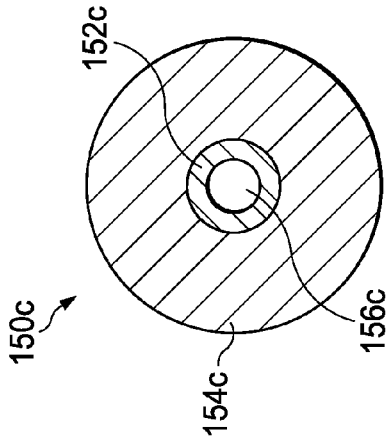


FIG. 2C

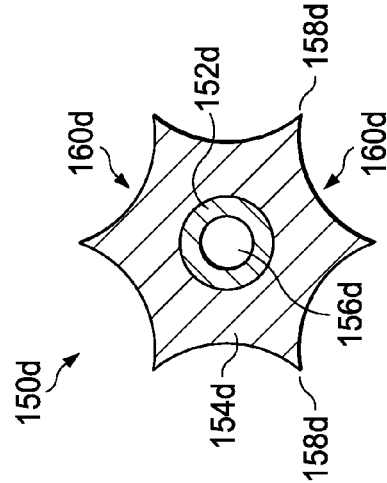


FIG. 2D

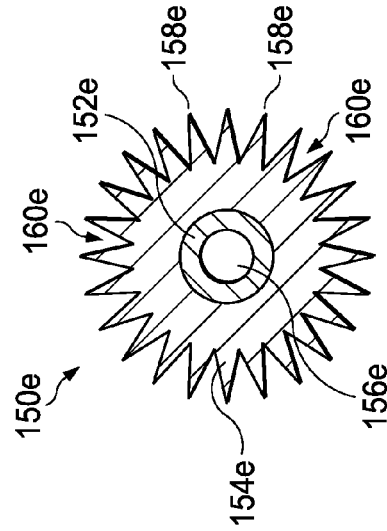


FIG. 2E

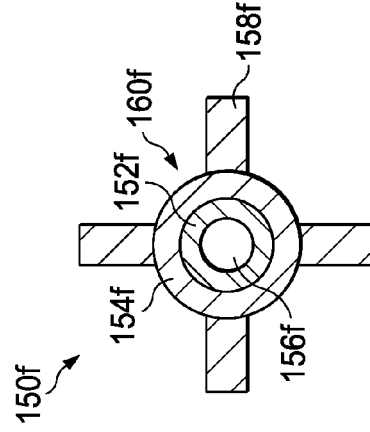


FIG. 2F

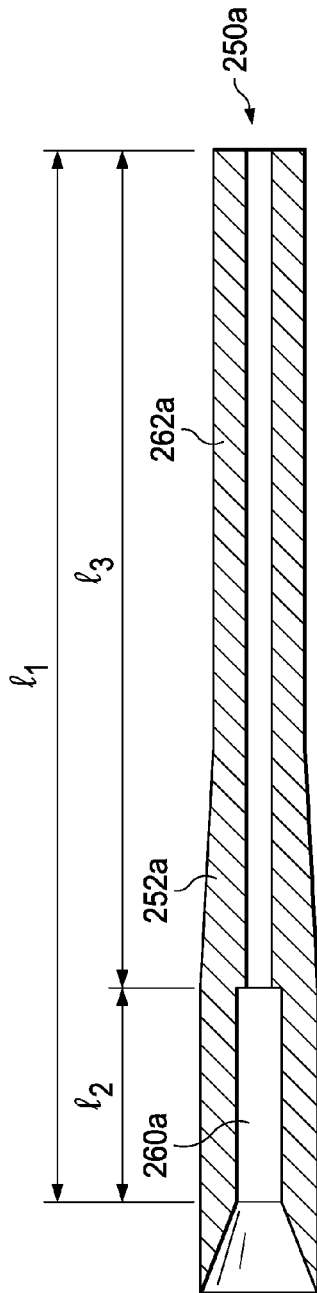


FIG. 3A

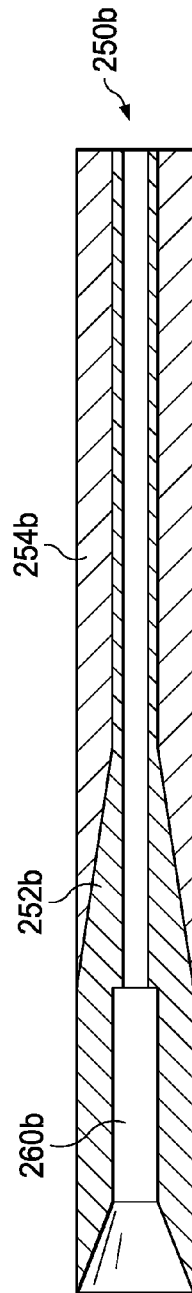


FIG. 3B

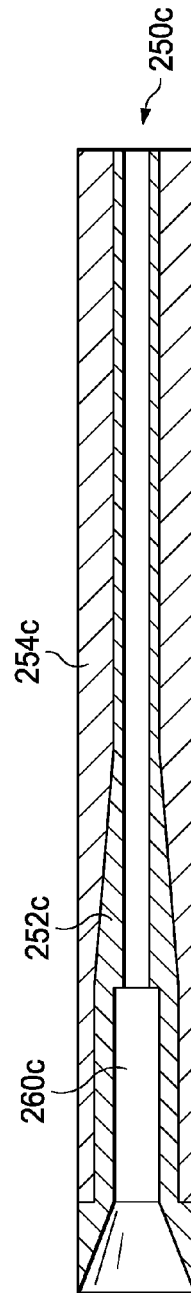


FIG. 3C

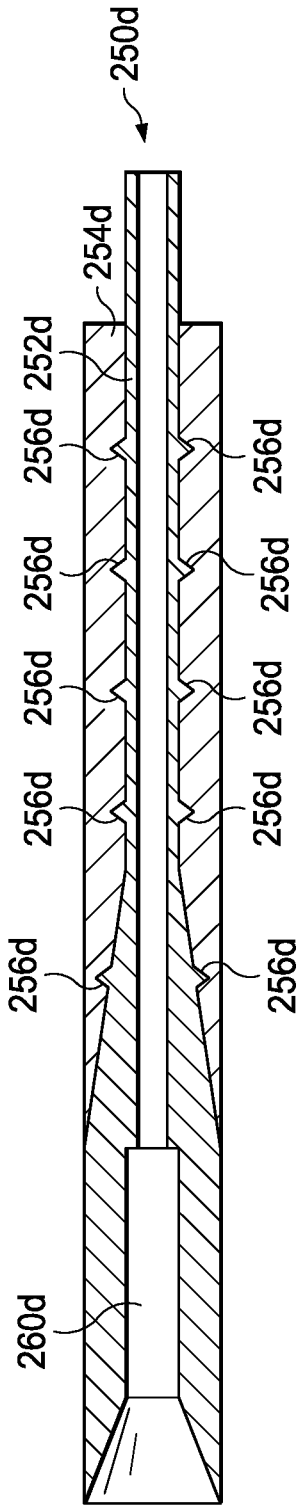


FIG. 3D

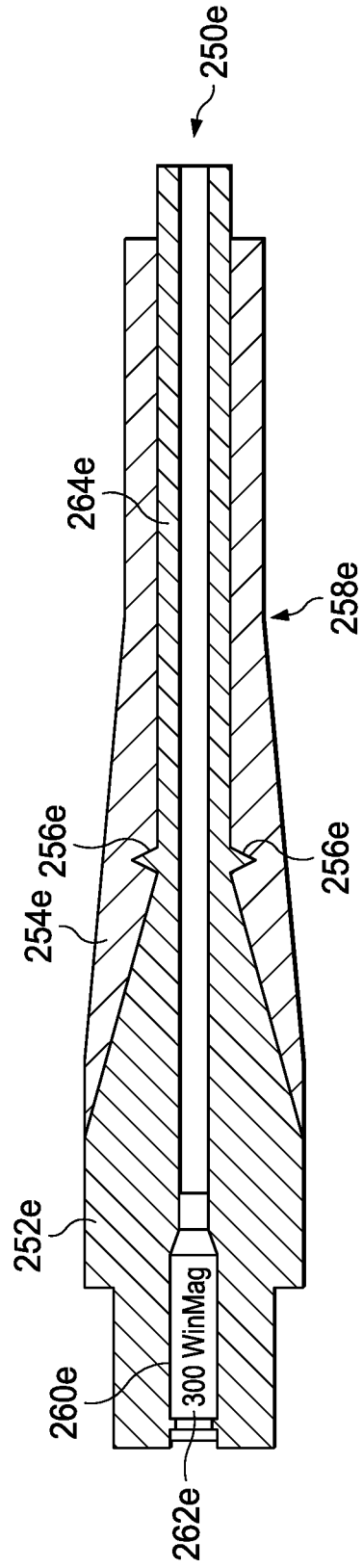


FIG. 3E

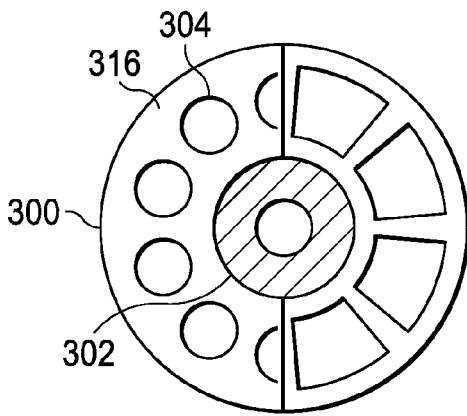


FIG. 4A

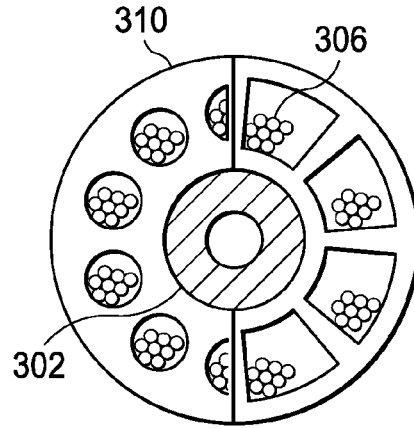


FIG. 4B

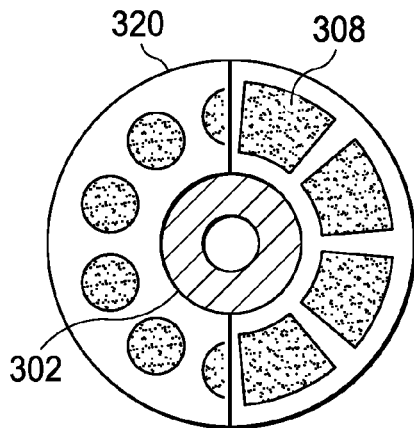


FIG. 4C

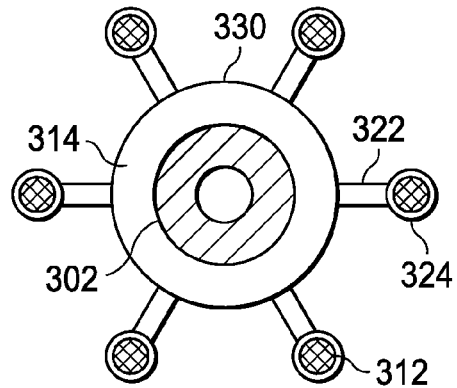


FIG. 4D

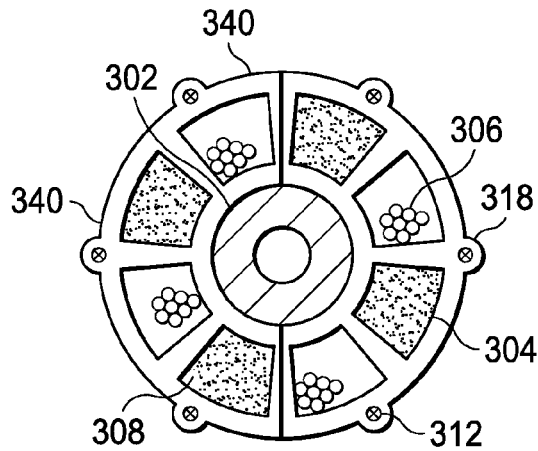


FIG. 4E

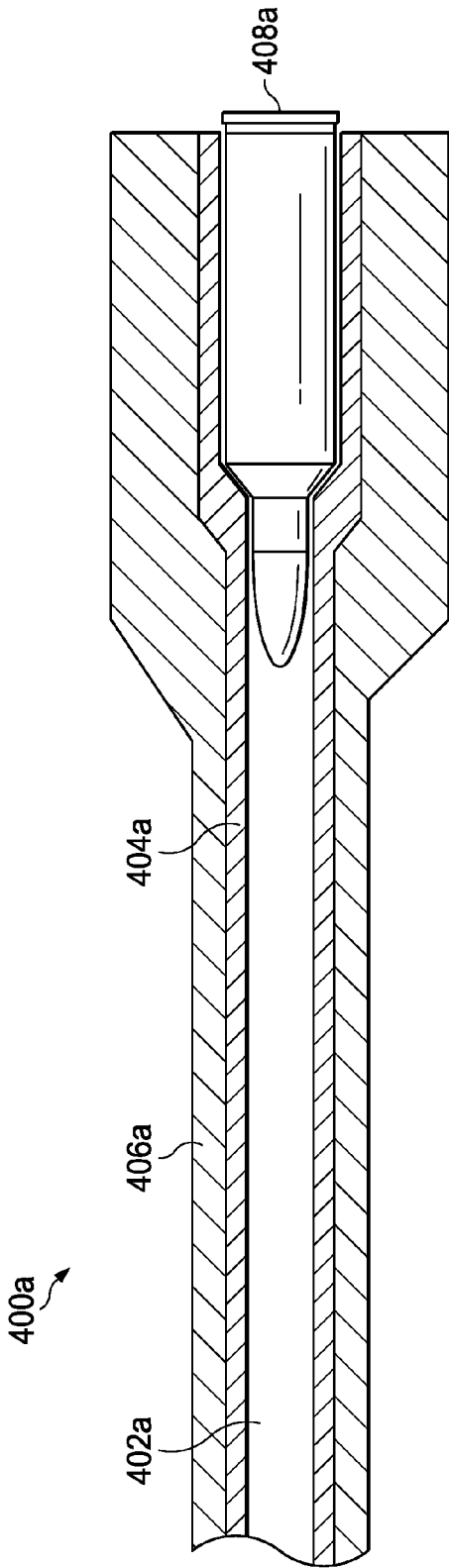


FIG. 5A

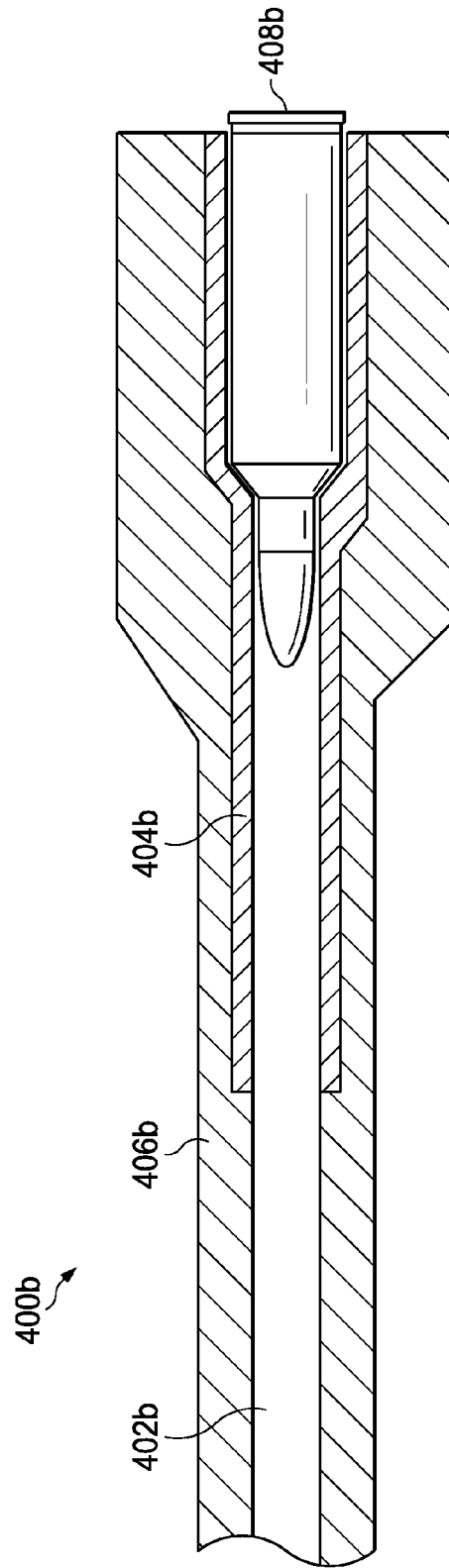


FIG. 5B

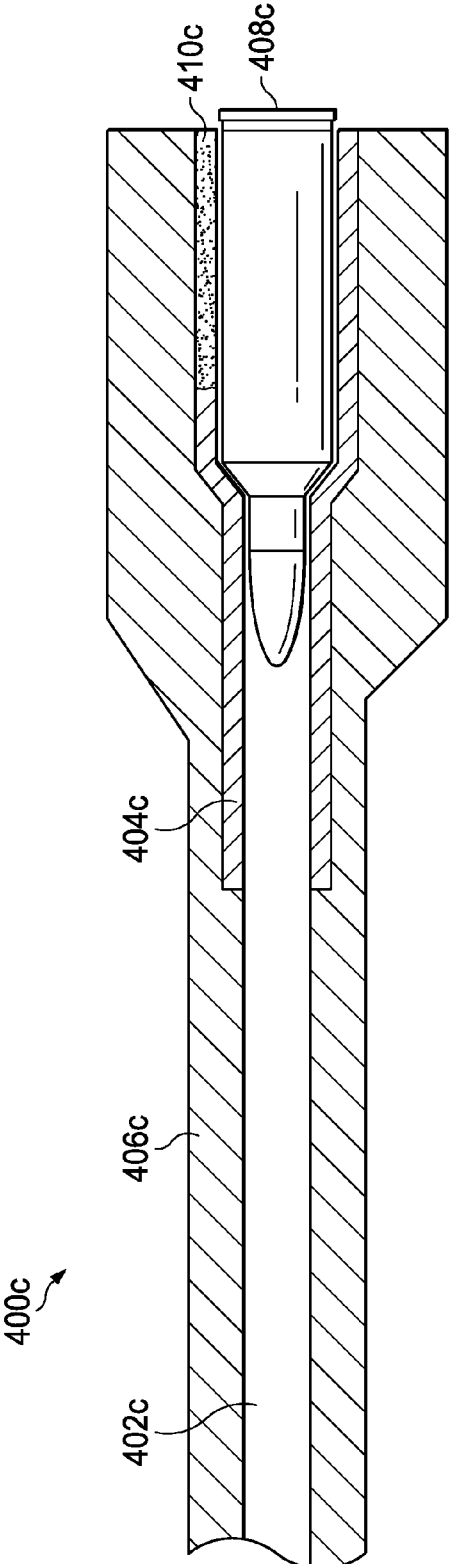


FIG. 5C

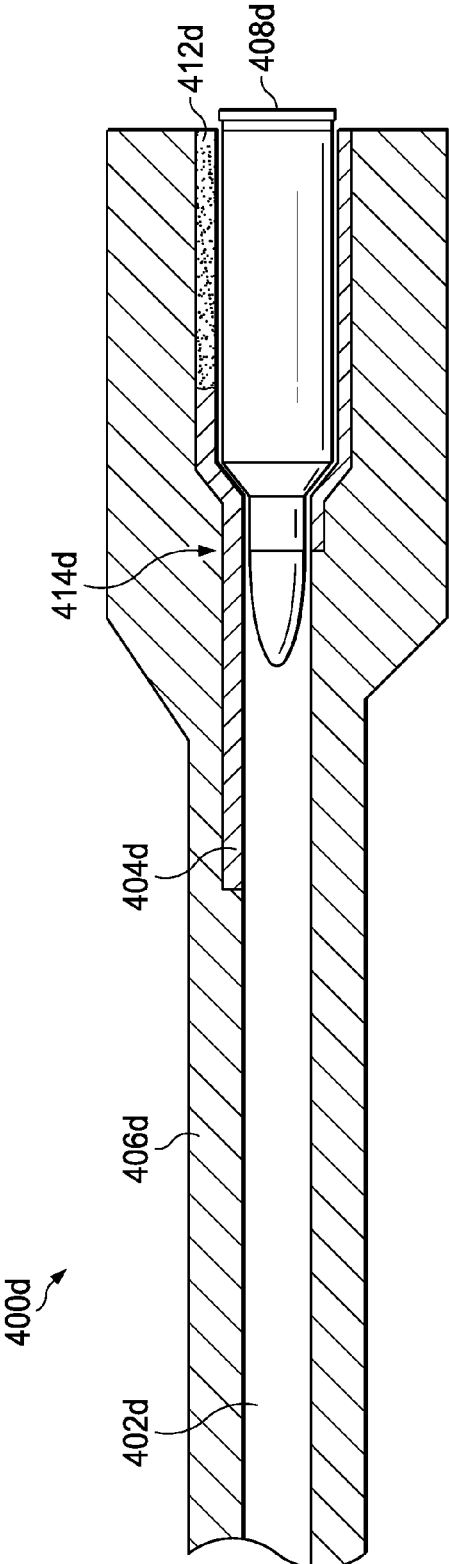


FIG. 5D

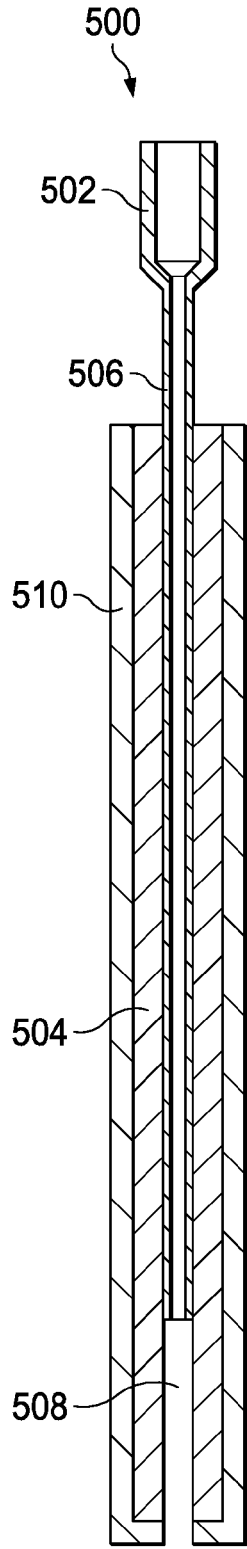


FIG. 6A

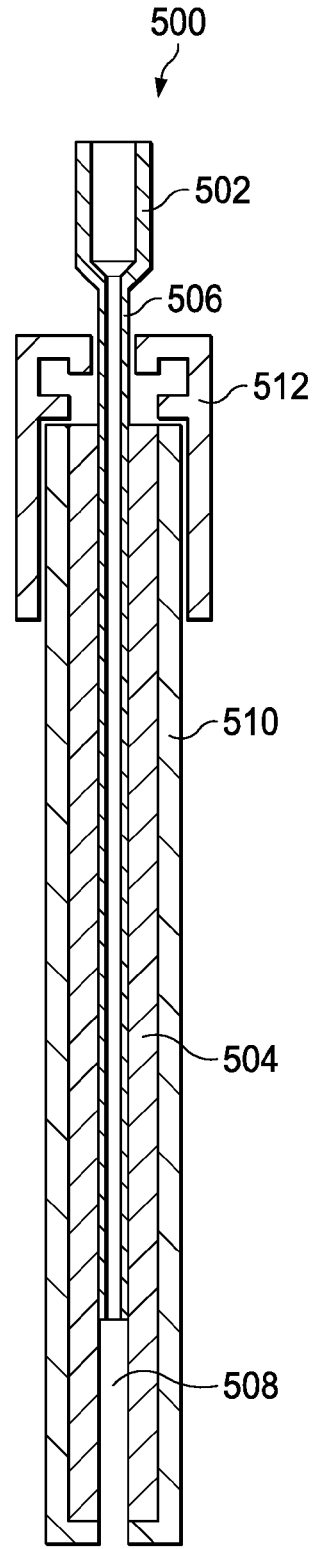


FIG. 6B

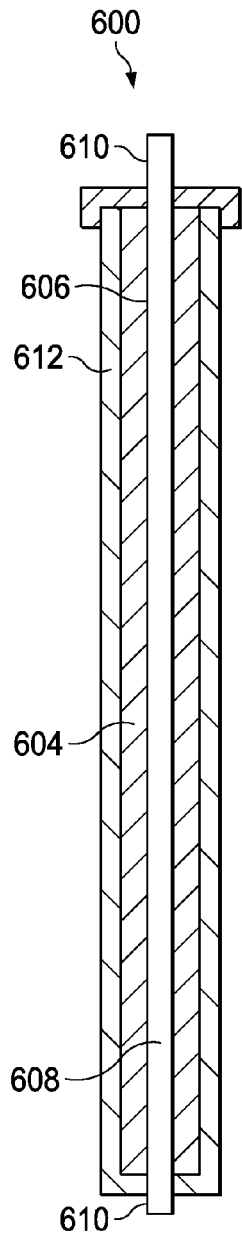


FIG. 7A

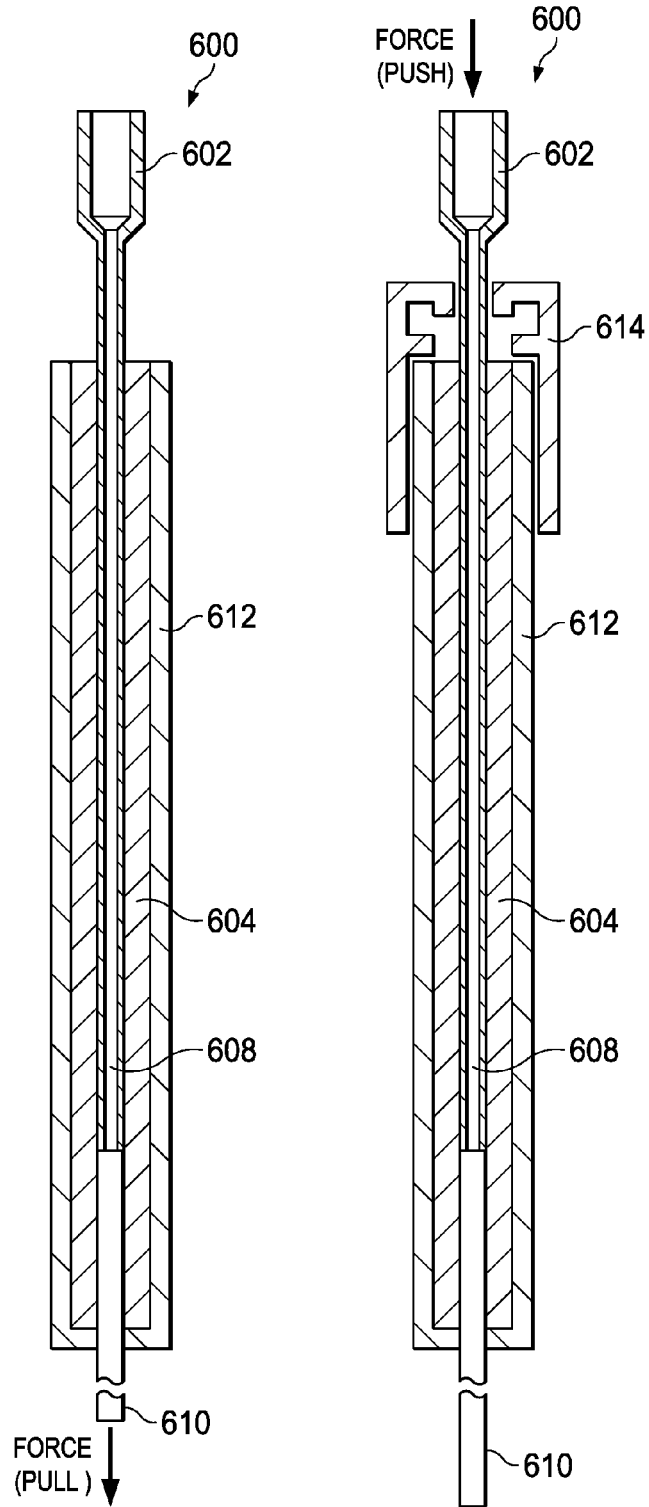


FIG. 7B

FIG. 7C

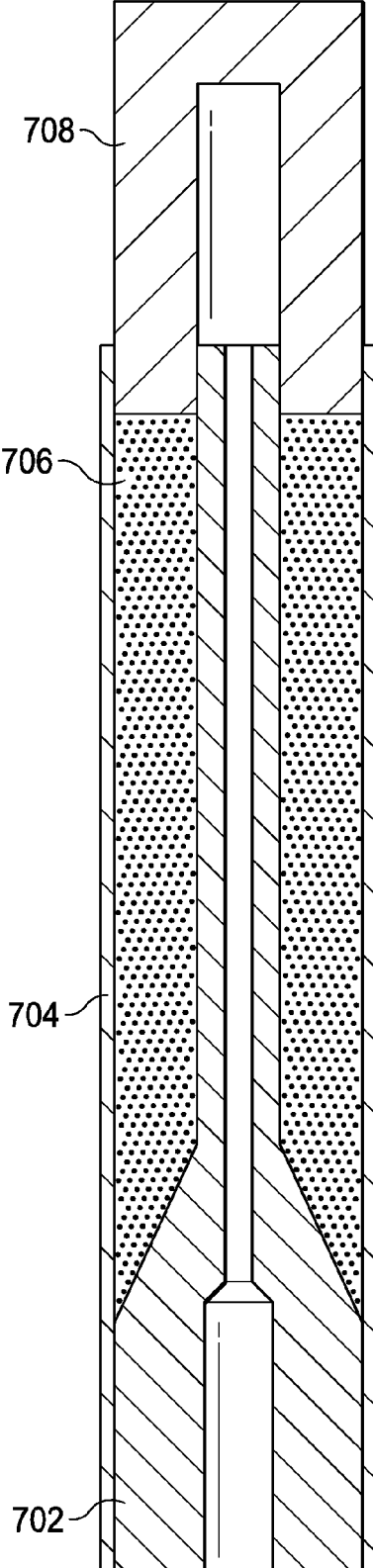


FIG. 8A

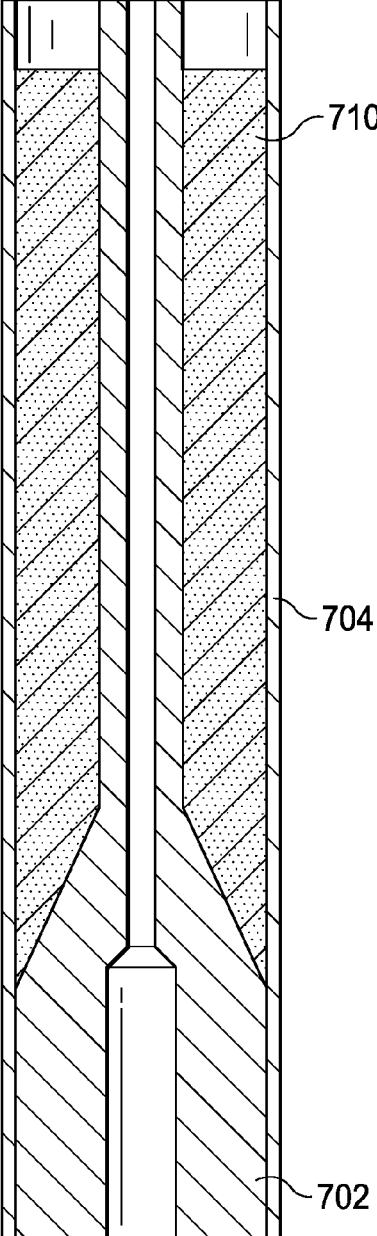


FIG. 8B

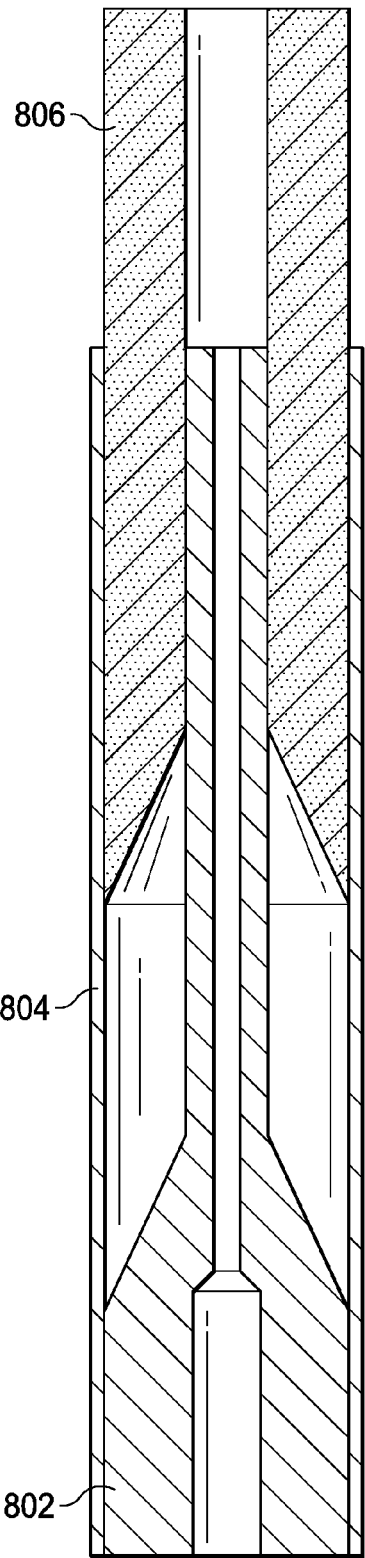


FIG. 9A

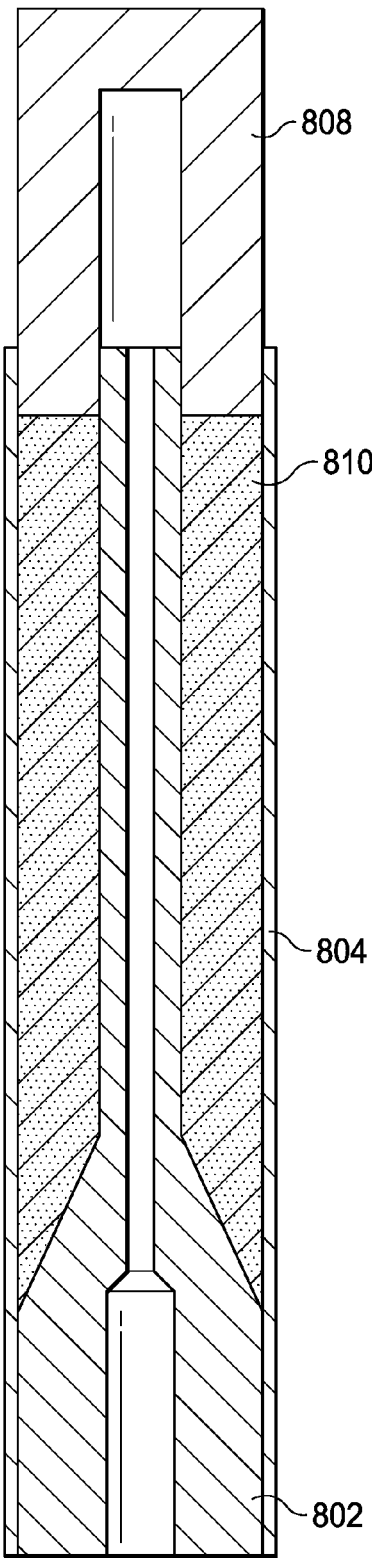


FIG. 9B

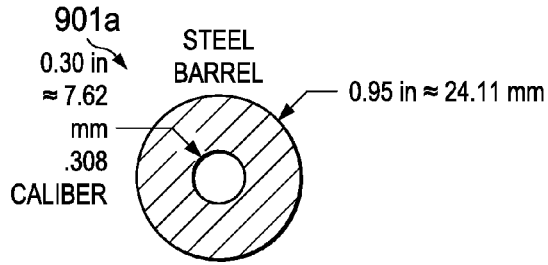


FIG. 10A

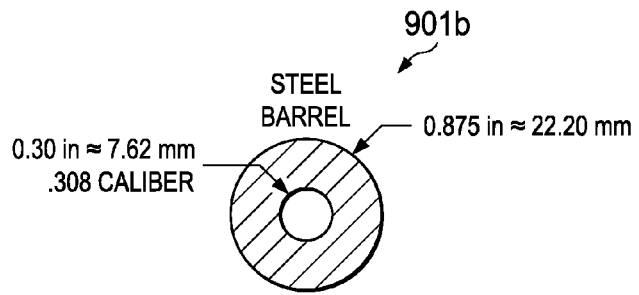


FIG. 10B

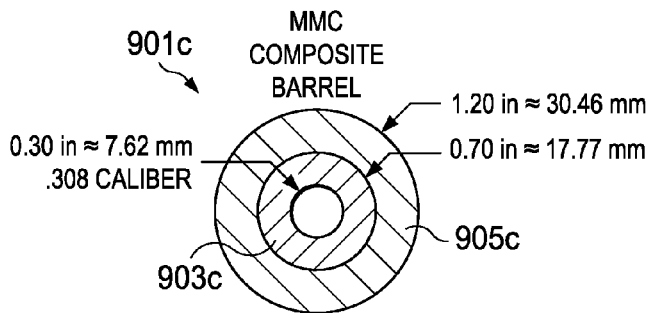


FIG. 10C

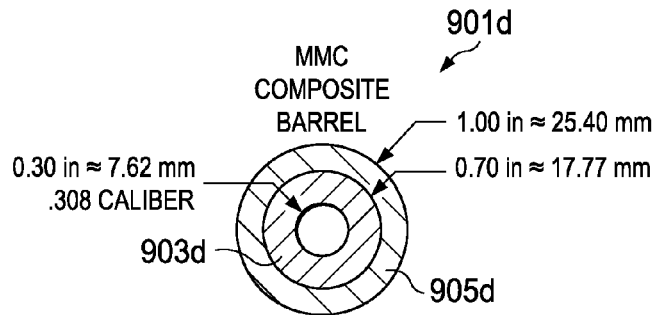
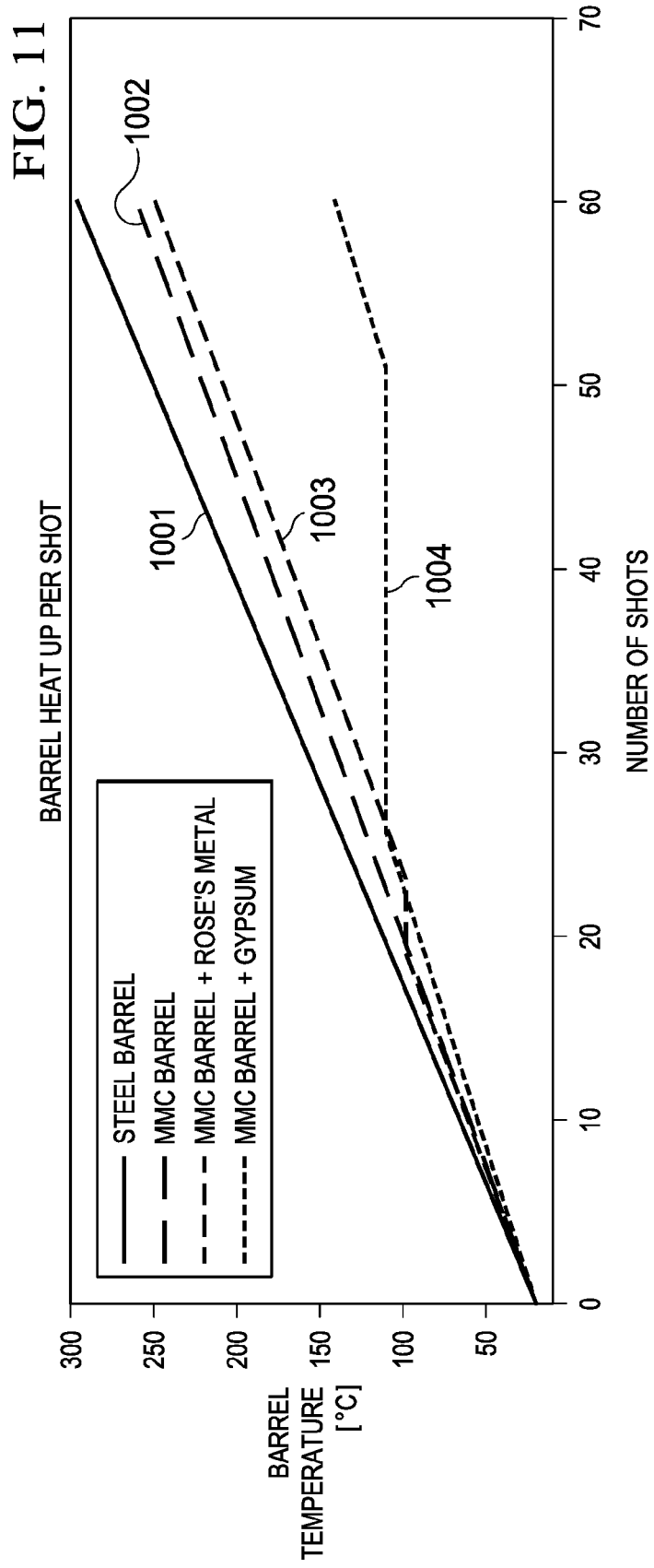


FIG. 10D



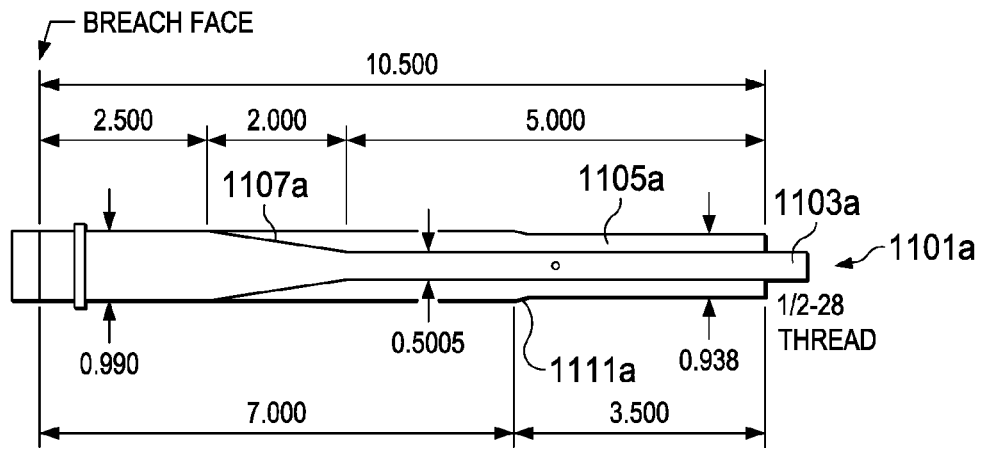


FIG. 12A

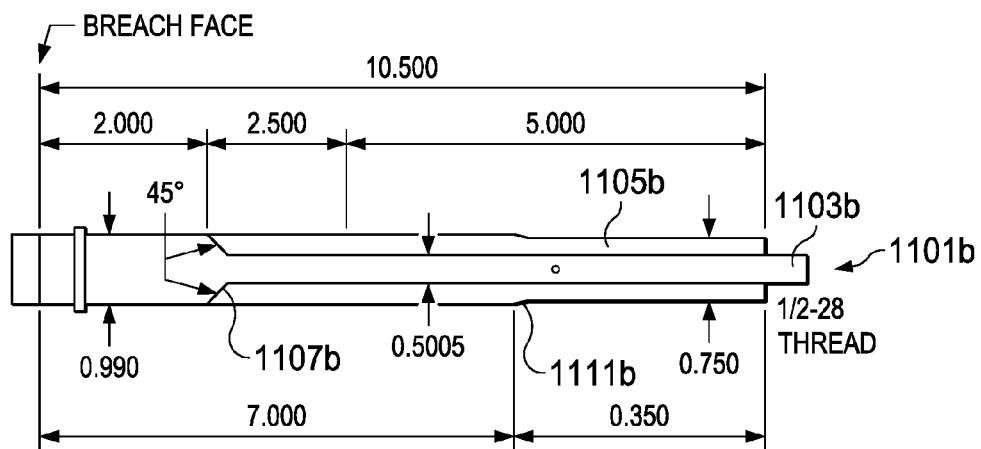


FIG. 12B

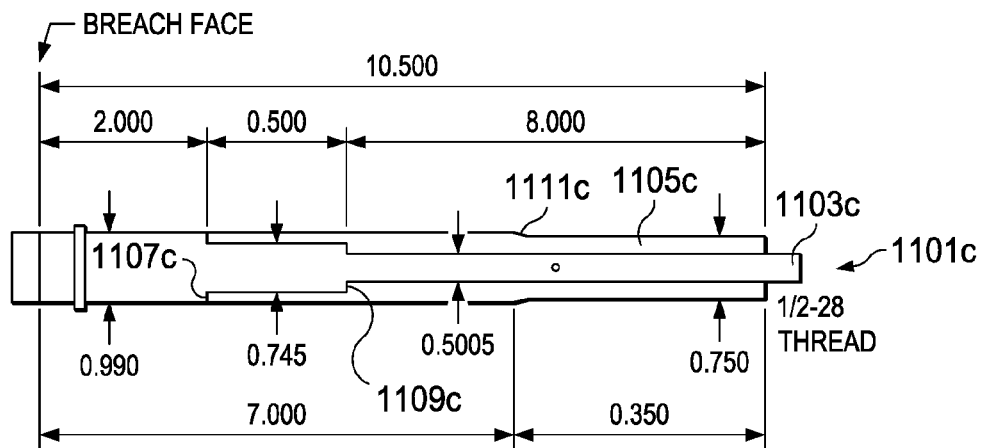


FIG. 12C

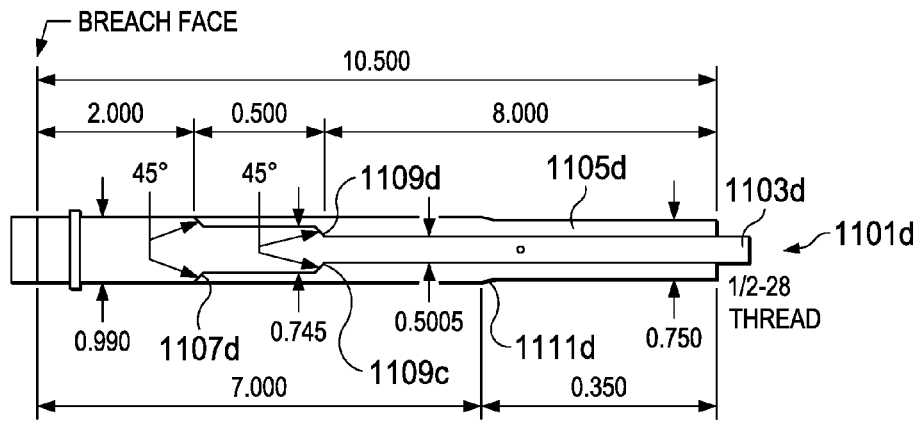


FIG. 12D

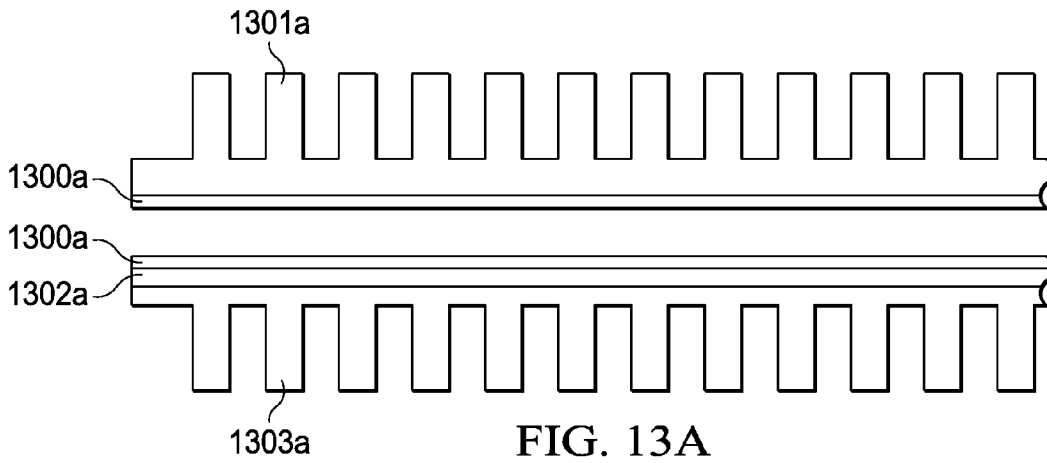


FIG. 13A

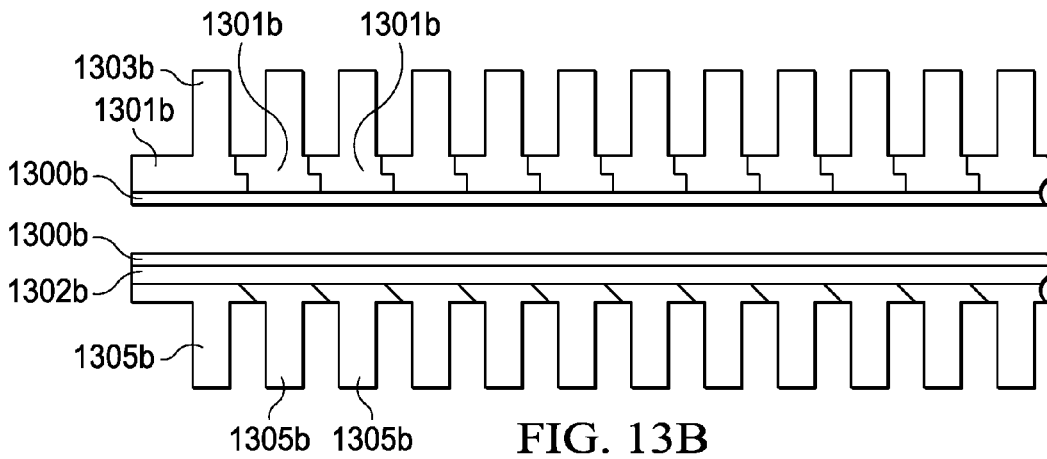


FIG. 13B

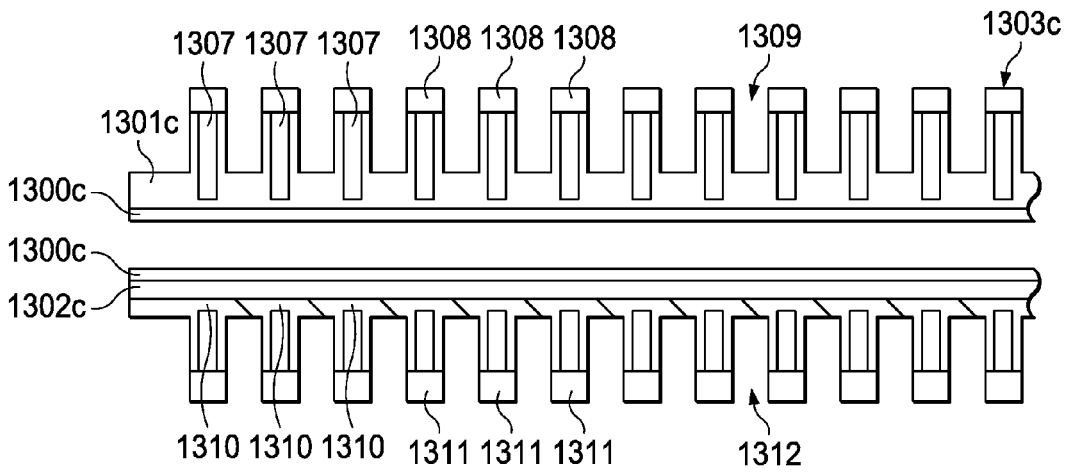


FIG. 13C

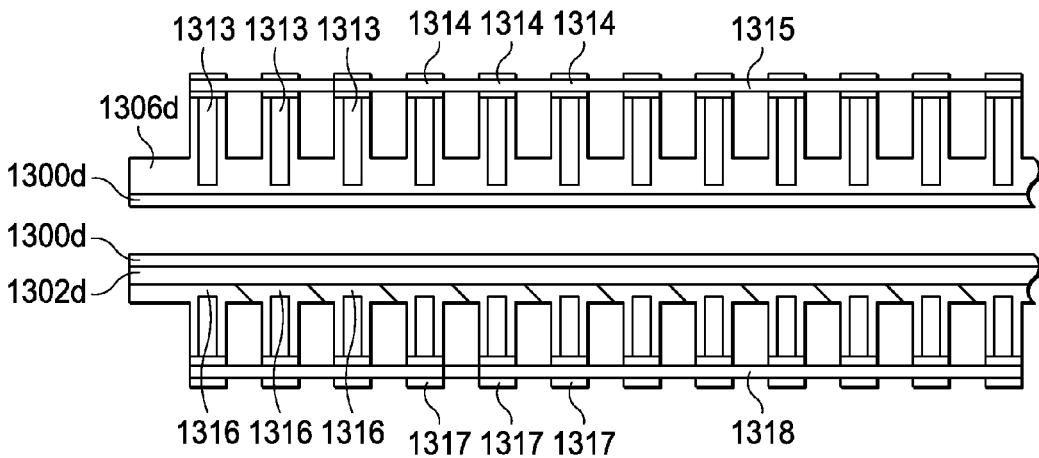
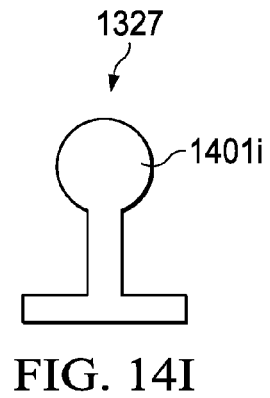
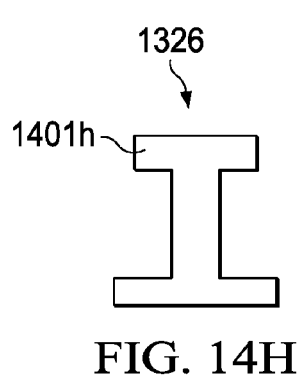
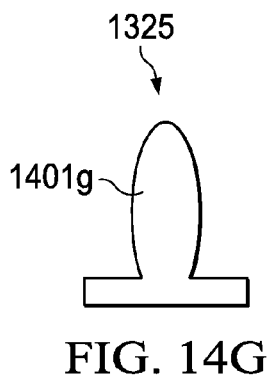
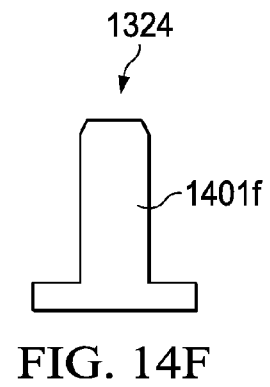
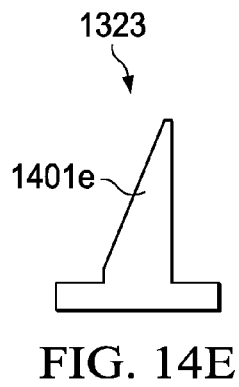
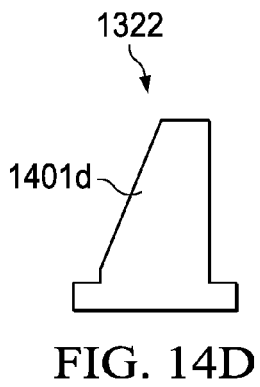
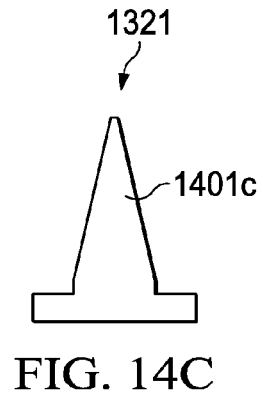
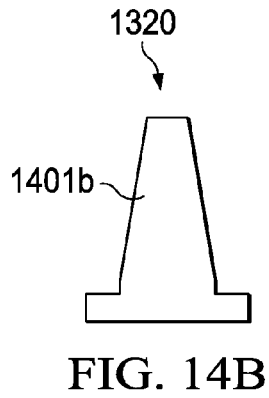
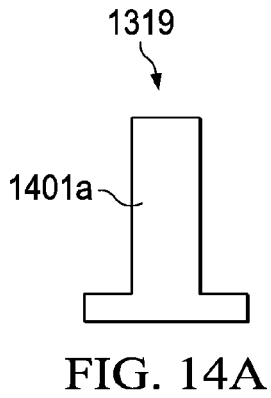


FIG. 13D



**ENHANCED METAL-METAL-MATRIX
COMPOSITE WEAPON BARRELS AND
WAYS OF MAKING THE SAME**

CROSS REFERENCE TO PRIOR APPLICATION

[0001] This application claims priority to and the benefit thereof from U.S. Provisional Patent Application No. 62/306,375 filed on Mar. 10, 2016, titled “ENHANCED METAL-METAL-MATRIX COMPOSITE WEAPON BARREL,” the entirety of which is hereby incorporated herein by reference.

FIELD OF THE DISCLOSURE

[0002] The present disclosure relates generally to composite weapon parts, their design and materials used in the fabrication of ballistic weapons and, more particularly, barrels for use with ballistic and non-ballistic weapons.

BACKGROUND

[0003] Certain weapons, including mortars, canons, machine and Gatling guns, railguns, long range, bolt, automatic, and semi-automatic rifles, may experience heating when firing. This heating can result then in deformation of the barrel, which in turn can degrade the accuracy of the weapon. In applications in which accuracy is paramount, e.g., in a firefight or a sniper setting, deformation due to heating can compromise the effectiveness of the weapon.

[0004] To enhance the ability of weapon barrels to dissipate heat and thereby maintain accuracy through periods of extended, high-frequency firing, a number of enhancements are provided to maintain barrel shape and rigidity as the gun barrel experiences heating, cooling and mechanical agitation such as vibration and recoil. The disclosed enhancements improve the ability of the gun barrel to quickly dissipate heat, to dampen barrel whip and increase stiffness, thereby further mitigating the negative effects of heating and vibrations induced by rapid firing. The enhancements include material compositions and suitable material combinations, part designs and combinations as well as methods of manufacturing the barrel and joining parts.

SUMMARY

[0005] In accordance with an illustrative embodiment, a gun has a composite gun barrel having an inner core and at least one outer sleeve that surrounds the circumference of the core over a length of the core, with the sleeve being joined to the core over such length.

[0006] In accordance with another illustrative embodiment, a method of manufacturing a gun barrel is disclosed. The gun barrel includes an inner core and at least one outer sleeve that surrounds the circumference of the core over a length of the core. The sleeve is joined to the core over such length. The illustrative method includes providing the core and the sleeve, wherein an internal diameter of the sleeve is smaller than an external diameter of the core. The method further includes heating the sleeve to a first temperature that is greater than the temperature of the core such that the internal diameter of the sleeve is slightly less than the external diameter of the core at the first temperature, and pressing the core into the internal diameter of the sleeve. In addition, the method includes allowing the core and the sleeve to reach thermal equilibrium, such that cooling of the

sleeve results in the formation of a compressive joint between the core and the sleeve.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The following figures are included to illustrate certain aspects of the present disclosure, and should not be viewed as exclusive embodiments. The subject matter disclosed is capable of considerable modifications, alterations, combinations, and equivalents in form and function, without departing from the scope of this disclosure.

[0008] FIG. 1 shows a schematic, perspective view of an exemplary weapon, namely a sniper rifle;

[0009] FIGS. 2A-2F show schematic, radial cross-sections of embodiments of a conventional weapon barrel and weapon barrels in accordance with the illustrative embodiments;

[0010] FIGS. 3A-3E show schematic, longitudinal cross-sections of a conventional weapon barrel and weapon barrels in accordance with the illustrative embodiments;

[0011] FIGS. 4A-4E show schematic, radial cross-sections of embodiments of weapon barrels in accordance with the illustrative embodiments, wherein FIGS. 4A, 4B, 4C, and 4F include vertical dividing lines such that each half of the figure may illustrate an alternative embodiment;

[0012] FIGS. 5A-5D show schematic, longitudinal cross-sections of weapon barrels in accordance with the illustrative embodiments;

[0013] FIGS. 6A-6B show schematic, longitudinal cross-sections of weapon barrels to illustrate a first process for fabricating a weapon barrel in accordance with an illustrative embodiment;

[0014] FIGS. 7A-7C show schematic, longitudinal cross-sections of weapon barrels to illustrate a second process for fabricating a weapon barrel in accordance with an illustrative embodiment;

[0015] FIGS. 8A-8B show schematic, longitudinal cross-sections of weapon barrels to illustrate a third process for fabricating a weapon barrel in accordance with an illustrative embodiment;

[0016] FIGS. 9A-9B show schematic, longitudinal cross-sections of weapon barrels to illustrate a fourth process for fabricating a weapon barrel in accordance with an illustrative embodiment;

[0017] FIGS. 10A-10D show schematic, radial cross-sections of steel barrels and MMC composite barrels for a similar caliber of weapon;

[0018] FIG. 11 is a graph showing calculated heat for four different barrels; and

[0019] FIGS. 12A-12D show schematic, longitudinal cross sections of a plurality of barrel configurations in accordance with the illustrative embodiments.

[0020] FIGS. 13A-13D show schematic, longitudinal cross sections of a plurality of embodiments barrels having annular fins.

[0021] FIGS. 14A-14I illustrate alternative embodiments of annular fin profiles.

DETAILED DESCRIPTION

[0022] In the following detailed description of the illustrative embodiments, reference is made to the accompanying drawings that form a part hereof. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is understood that other

embodiments may be utilized and that logical structural, mechanical, electrical, and chemical changes may be made without departing from the spirit or scope of the invention. To avoid detail not necessary to enable those skilled in the art to practice the embodiments described herein, the description may omit certain information known to those skilled in the art. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the illustrative embodiments is defined only by the appended claims.

[0023] The present disclosure relates generally to firearms having a barrel core surrounded with a sleeve in such a way as to improve the firearm's stiffness without excessive increases in weight. Conventional barrels having increased thickness for improved stiffness and accuracy are known as heavy or bull barrel profiles and may be found in, for example, sniper rifles. Such conventional barrels are typically made from homogeneous metal alloys, usually steels (iron alloys/ferrous alloys) and nickel alloys.

[0024] The barrel portion of a firearm is generally built to withstand the pressure of the firing load and the bullet while providing enough stiffness for sufficient accuracy. This criteria may be achieved simply using a barrel of high or increased wall thickness, as increasing wall thickness increases the maximum pressure load the barrel can bear and also improves stiffness by virtue of enlarged barrel diameter and correspondingly increased second moment of area. These advantages are offset by a corresponding increased barrel weight, which may detract from the wieldability and usability of the weapon.

[0025] To that end, an enhanced weapon barrel and methods of fabrication of such weapon barrels are disclosed that have an increased diameter without the expected corresponding increase in barrel weight. Indeed, in some embodiments, barrel weight may even be decreased even where the outer diameter of the weapon barrel is increased.

[0026] One method for fabricating a weapon barrel that is light in weight while also having an increased diameter (as opposed to a conventional, single-material barrel) is to create a metallic barrel having a thin wall thickness and to wrap the barrel with a carbon fiber composite. Such composites usually consist of a resin matrix based on epoxy resins. Carbon fiber composites provide the advantage of being light-weight and strong (normally having a specific tensile strength higher than steels and nickel alloys). A carbon fiber-wrapped barrel may therefore be lighter than a conventional barrel made from a steel or similar metal barrel. Such barrel configurations, however, may have the disadvantage of low thermal stability. Low thermal stability effectively restricts use of such barrels in semi or fully automatic weapons to a few close-together shots. The low thermal stability also results in limiting deployment of the barrel to systems in which the temperature of the barrel doesn't rise above 100° C. for extended periods of times. At higher temperatures, the organic resin matrix will degrade permanently. Moreover, carbon fiber composite wraps also act as an insulator due to their low thermal conductivity. Conventional carbon fiber therefore limits the ability of the barrel to dissipate heat, which may in turn detract from the precision of the weapon by facilitating thermal barrel creep.

[0027] Other types of multi-material barrels may be found in smooth-bore cannons, such as those deployed in Abrams and Leopard II battle tanks. These barrels actually have an insulating outer layer for thermal management. The insulat-

ing layer increases barrel diameter, but unlike the aforementioned carbon fiber outer layer, does not enhance the mechanical integrity or stiffness of the barrel.

[0028] Another form of a multilayered barrel includes an outer metal sleeve, with a void between the barrel and the sleeve being sealed with a light, hardening filler material. Such fillers may, however, be poor thermal conductors and may therefore contribute to hot spots and thermal creep. Such barrels may be ill-suited for use in semi and fully automatic weapons because the sustainable rate of fire would be reduced to prevent overheating and thermal creep. Also, the sleeve may be susceptible to separation from the filler material and barrel due to differential rates of thermal expansion, thereby compromising the barrel's mechanical integrity and accuracy.

[0029] The embodiments described herein address the aforementioned issues by providing for structures, sleeve materials, material compositions, and corresponding manufacturing and joining techniques for enhanced weapon barrels that perform well as low cadence weapons (e.g. bolt action rifles) and as high cadence weapons (e.g., Gatling guns, machine guns and automatic rifles). The disclosed embodiments offer enhancements in terms of weight reduction, improved thermal performance and improved accuracy (or a combination of the foregoing) relative to conventional weapon barrels.

[0030] The embodiments of composite weapon barrels described herein offer improved thermal performance and rigidity with little or no increase in weight as compared to traditional barrels, as described below with respect to Examples 3 and 4. Turning now to the figures, FIG. 1 shows an exemplary weapon 100 (shown here as a sniper rifle) in accordance with the illustrative embodiments. The weapon 100 is illustrated as a sniper rifle. It is noted, however, that the concepts described herein may be similarly applicable to other types of weapons, e.g. bolt-action rifles, fully and semi-automatic rifles, mortars, canons, etc. The weapon 100 includes a barrel 102. The barrel 102 may be formed using any of the embodiments described herein and in accordance with any combination of the features of the various embodiments. To that end, a number of illustrative cross-sections, which may be perceived as being taken along section lines A-A of FIG. 1, are shown and described below.

[0031] A first group of embodiments of barrels 102 are shown in FIGS. 2A-2C. FIG. 2A shows a conventional barrel 150a, having a single material barrel core 152a. In the embodiments of FIGS. 2B-2F, the core 152(b-f) is shown as being joined to and enclosed within a sleeve 154(b-f). For example, FIG. 2B shows a composite barrel 150b, having an inner core 152b and an outer sleeve 154b. In the embodiment of FIG. 2B, the thickness of the sleeve 154b is slightly greater but comparable to the thickness of the core 152b. FIG. 2C shows a composite barrel 150c, having an inner core 152c and an outer sleeve 154c. In the embodiment of FIG. 2C, the thickness of the sleeve 154c is much greater than (by approximately a factor of 5) the thickness of the core 152c.

[0032] Additional embodiments are shown in FIGS. 2D-2F. In FIG. 2D, the core 152d is shown as being cylindrical and the sleeve 154f is shown as having the shape of a six-pointed star, with arcuate sections 156d between points 158d. FIG. 2E shows a similar embodiment, in which the sleeve 154e surrounding the core 152e has a larger number of elongated fins 158e separated by gaps 156e. In

this embodiment, the fins **158e** are operable to conduct heat away from the core **152e** and offer increased surface area to dissipate heat generated by firing of the weapon to the external environment. FIG. 2F shows a similar embodiment of a barrel **150f** in which the core **152f** is joined to and surrounded by sleeve **154f**. The sleeve **154f** has a cylindrical portion **160f** coupled to or formed integrally with fins **158f** spaced at ninety degree intervals about the circumference of the barrel **150f**.

[0033] Referring again (for illustrative purposes) to FIG. 2B, the barrel **150b** is formed from a barrel core **152b** surrounded by sleeve **154b**. The sleeve **154b** may be a lightweight, thermally conductive sleeve **154b** made from one or more metal-matrix composite (MMC) materials. Such materials may also be referred to as metal-matrix materials. In the illustrative embodiment of FIG. 2C, the increased diameter of the sleeve **154c** improves the barrel's stiffness and the sleeve's ability to conduct heat from the barrel core **152c** and distributes the heat more evenly along the external surface of the barrel **150c**. In such embodiments, hot spots are reduced and more surface area can contribute to heat dissipation.

[0034] The increased diameter also allows integration of phase changing and/or vibration dampening materials. Examples of phase change materials include materials well-suited for latent heat storage, such as salts, polymers, paraffins and waxes, calcium sulfate, fusible metal alloys like Rose's metal, and Galinstan. Correspondingly, examples of vibration dampening materials include springs, granular or powdery matter like sand, lead shot and non-Newtonian fluids. The use of phase change materials may improve barrel performance by allowing several consecutive shots to be taken at the same barrel temperature and thereby preventing thermal creep of the barrel (see discussion of Example 5). Similarly, the use of vibration dampening materials may help to reduce recoil, and aid user comfort and accuracy. The increased barrel diameter further allows efficient surface patterning to increase the surface-to-specific heat ratio and thereby improves the cooling efficiency of shaped barrels, such as those described with regard to FIGS. 2D-2F.

[0035] It is noted that while the above-mentioned embodiments depict longitudinal structures that extend over at least a portion of the barrel's length, radial structures are also contemplated as an aspect of this disclosure. To that end, each of the longitudinal features of, for example, FIGS. 2c (fins **158f**) and 4A-4E may alternatively be implemented as radial or annular structures (e.g., ring-shaped structures) that are placed at intervals along the length of the barrel to increase surface area and to otherwise enhance cooling properties.

[0036] FIGS. 13A-13E show a plurality of embodiments of longitudinal barrel cross sections having annular fins. The top portion of FIG. 13A shows an embodiment having a sleeve **1301a** that has annular fins **1303a**. The annular fins **1303a** have a rectangular cross-section and the sleeve **1301a** is directly joined with the barrel core **1300a**. Such a profile can be machined into a sleeve or manufactured near-net-shape with a HIP manufacturing technique, as described below. This configuration provides stiffness, pressure resistance and increased surface area. In some embodiments, as shown in the lower portion of FIG. 13A, an optional intermediate layer **1302a** of a material with a thermal expansion coefficient larger than that of the sleeve **1301a**

and core **1300a** can be added to enhance mechanical integrity during thermal shrinking and expansion, as described previously.

[0037] The top portion of FIG. 13B shows an embodiment having a sleeve **1301b** that has annular fins **1303b** and is analogous in most respects to the embodiment of the top portion of FIG. 13A. The annular fins **1303b** have a rectangular cross-section and the sleeve is directly joined with the barrel **1300b**. Here, the sleeve is made up of a plurality of sleeve segments **1301b**, each of which may be joined together to form a continuous sleeve. The sleeve segments **1301b** may be a plurality of interlocking segments or, as shown with respect to the embodiment of the lower portion of FIG. 13B, a plurality of overlapping segments **1305b**. The aforementioned segments may be assembled by shrink-fitting, soldering, gluing, fasteners, or another suitable joining method that provide a suitable thermal coupling to the barrel core **1300b**.

[0038] The top portion of FIG. 13C shows an embodiment having a sleeve **1301c** that has annular fins **1303c** and is analogous in most respects to the embodiment of the top portion of FIG. 13A. The annular fins **1303c** have a rectangular cross-section and the sleeve is directly joined with the barrel **1300c**. Here, the annular fins **1303c** are formed with voids **1307** that can be filled with phase changing materials or other filler materials to tune the thermal or dampening properties of the barrel. Subsequent to filling, caps **1308** may be used to enclose the filler material. The embodiment of the lower portion of FIG. 13C is analogous in most respects to that of the upper portion, except that the sleeve is made up of a plurality of overlapping segments **1310** that may be joined to an intermediate layer **1302c** to form a sleeve. Gaps **1309** and **1312** are positioned between the annular fins to facilitate airflow and heat transfer. For similar reasons, the caps **1308** and **1311** may be omitted to further increase exposed surface area.

[0039] The embodiments of the top portion and bottom portion of FIG. 13D, respectively, are analogous to the embodiments of FIG. 13C, with the exception that the caps **1314** and **1317** include passages to receive stiffening rods **1315** and **1318**, which extend through the caps **1314** and **1317** of the annular fins **1313** and **1316**.

[0040] FIGS. 14A-14I illustrates alternative embodiments of fin profiles that may be used to form the aforementioned annular fins. Each profile provides different gripping and heat transfer properties. To that end, FIG. 14A illustrates an annular fin having a rectangular profile **1401a**; FIG. 14B illustrates an annular fin **1401b** having a flattened, partial conical profile; FIG. 14C illustrates an annular fin **1401c** having a triangular profile; FIG. 14D illustrates an annular fin **1401d** having an asymmetrical flat cone profile FIG. 14E illustrates an annular fin **1401e** having an asymmetrical triangle profile; FIG. 14F illustrates an annular fin **1401f** having a rounded rectangular profile; FIG. 14G illustrates an annular fin **1401g** having an ovoid profile; FIG. 14H illustrates an annular fin **1401h** having a T-shaped profile; and FIG. 14I illustrates an annular fin **1401i** having a partially rectangular profile with a bulb-shape profile placed atop a rectangular portion of the annular fin **1401i**. Assembled, the annular fin embodiment may appear as discs, cylinders, stubs, or spikes extending radially from a gun barrel.

[0041] Referring again to FIG. 2B, the materials used to fabricate the components of the barrel (e.g., barrel **150b**) may be selected such that the material properties enable the

components to function or to be assembled in a complementary fashion. For example, thermal expansion coefficients of the sleeve **154b** and core **152b** may be selected to provide for a suitable joint between the sleeve **154b** and core **152b**. In the preferred embodiments, the sleeve **154b** and core **152b** are both mechanically coupled and thermally coupled. To that end, the sleeve **154b** may be joined to the core **152b** by a suitable manufacturing technique to provide a high degree of coupling. Examples of such manufacturing techniques include hot isotactic pressing (HIP), explosion welding and shrink fitting. In the case of shrink fitting, the sleeve **154b** may be heated to a very high temperature and fitted around the core **152b**. In accordance with other techniques, (e.g., additive manufacturing or sintering), the sleeve **154b** may be consolidated from a powder that fuses together around the core **152b**. Other methods (e.g., press-fitting) and retrofitting are also discussed below. In a preferred embodiment, fabrication of the barrel **150b** includes forming a joint that gives structural and thermal integrity over the whole operating temperature range of the barrel **150b** when the barrel **150b** is in use at the highest expected cadence.

Metal-Matrix Material Properties and Components

[0042] Barrels utilizing the technology disclosed herein provide a number of advantages with respect to mechanical and thermal properties. In accordance with the illustrative embodiments, a weapon barrel is disclosed that utilizes a core and sleeve design to form a composite barrel and methods to make the same. To that end, FIGS. 3A-3D show longitudinal cross-sections of barrel embodiments. FIG. 3A shows a conventional barrel **250a** made from a single material core **252a**. Here, l_1 indicates the length of the overall barrel assembly, including the barrel and breach, l_2 indicates the length of the breach **260a**, and l_3 indicates the length of the remainder of the barrel **250a** adjacent to the breach **260a**. As with the embodiments described above, the core **252a** may comprise a single material, such as steel. FIGS. 3B and 3C illustrate alternative embodiments of a gun barrel (**250b** and **250c**, respectively). In the embodiment of FIG. 3C, a sleeve **252c** is provided that extends over the barrel length l_2 , but terminates at the breach **260c**. Alternatively, in the embodiment of FIG. 3B, the sleeve **254b** extends over the entirety of the barrel **250b**, including the breach **260b**.

[0043] The embodiment of FIG. 3D is analogous in most respects to the embodiment of FIG. 3B. The sleeve **254d** extends over the breach **260b**. A portion of the core **252d**, however, extends through the sleeve **254d**. In addition, a ridge **256d** is included on the exterior of the core **252d** to engage the sleeve **254d** and to ensure that the sleeve **254d** remains fixed relative to the core **252d**. While the ridge **256d** is shown as having a triangular profile, in other embodiments, the ridge **256d** may have a rounded profile or a rectangular profile. In still other embodiments, the ridge **256d** may be replaced by a groove or detent. In addition, the sleeve **254d** may be formed to have a groove or protrusion that is sized to engage the ridge **256d** or detent of the core **252d**. Further, one or more ridges **256d** may be provided at the breach, in the case of an embodiment having a sleeve that extends over the breach, or spaced at regular or semi-regular intervals along the core.

[0044] It is noted that while the ridge **256d** is shown only with respect to the embodiment of FIG. 3D, it is contemplated that unless the described features are incompatible,

each feature from each of the described embodiments may be combined with other features described herein within the scope of this disclosure. For example, a barrel may be provided that includes a sleeve having a longitudinal cross-section that corresponds to the barrel shown in FIG. 3C, a ridge such as that described with regard to FIG. 3D, and a perpendicular cross-section that corresponds to the embodiment of the left side of FIG. 4B.

[0045] In the embodiment of FIG. 3E, an embodiment is shown in which the sleeve **254e** does not extend over the chamber **260e**. In this embodiment, the core **252e** and the sleeve **254e** have dissimilar shapes having distinct and functional differences. The core **252e** has a reduced thickness as well as a circumferential ridge/peak **256e** which further secures the sleeve **254e** when the barrel **250e** is assembled. It is noted that an optional intermediate layer **264e** may be included between the core **252e** and sleeve **254e**. In some embodiments, the sleeve **254e** has a different geometry from the core **252e**. The core **252e** is straight over most of its length while the sleeve **254e** tapers and has a step **258e** as the sleeve **254e** transitions from a first end to a step **258e**. At the first end, the sleeve **254e** has nominal thickness and an outer diameter that is comparable to the diameter of the core **252e**. At the step **258e**, the taper terminates and the sleeve **254e** has an outer diameter that is constant and larger than that of the core **252e** due to the expanded thickness of the sleeve **254e** until reaching a second end of the sleeve **254e**.

[0046] Other geometries are contemplated in FIGS. 12A-12D. Referring to FIG. 12A, for example, it is noted that in the sections of the barrel not covered by the sleeve, pressure resistance of the barrel derives solely from the core. In such embodiments, the transition from the exposed core to the sleeve-covered core can be realized in many ways. The embodiment of FIG. 12A, for example, shows a barrel **1101a** having a core **1103a** that extends past the end of sleeve **1105a**. The sleeve **1105a** is joined to the core **1103a** at a taper **1107a**, which may extend for about twenty percent of the length of the portion of the barrel **1101a** that extends beyond the breach face (near the left-hand end of the figure). The sleeve **1105a** has a small external shoulder **1111a** that is offset from the end of the sleeve **1105** (by, for example, approximately 3.5 inches). The embodiment of FIG. 12B is similar in most respects to the embodiment of FIG. 12A, with the exception that the taper **1107b** is shown as having a steeper (45°) angle.

[0047] FIG. 12C shows a barrel **1101c** that is similar in most respect but instead of a taper, includes a step design having a first step **1107c** and a second step **1109c** that is longitudinally offset from first step **1107c**. Each step **1107c** and **1109c** provides a flat surface that may be used to further anchor the sleeve **1105c** relative to the core **1103c**. In lieu of steps, the embodiment of barrel **1101d** of FIG. 12D shows offset, sequential tapers **1107d**, **1109d**, which are illustrated as forty-five degree tapers positioned at 2 units of measurement from the breach face and 2.5 units of measurement from the breach face, respectively. In each of the embodiments of FIGS. 12A-12D, the shoulder **1111a-d** is shown (for exemplary purposes) as being offset by 7 units of measurement from the breach face. Here, it is noted that the geometries of the cross-sections shown in FIGS. 12A-12D are shown only for illustrative purposes, and other dimensions and proportional relationships between the dimensions shown are also possible.

[0048] Referring again to FIG. 3B, the core **252b** may be made from any suitable ceramic, metallic, polymeric, organic, inorganic or composite material thereof, which can withstand the pressure and heat of firing. The core material may also be selected to withstand abrasion sustained as projectiles pass through the barrel bore **250b** without being too heavy or thick.

[0049] In the illustrative embodiments, the specific strength of suitable core materials may be (1) above 20 N·m/g, (2) better than 50 N·m/g, (3) better than 100 N·m/g, (4) between 200 N·m/g to 500 N·m/g, (5) better than 700 N·m/g, or (6) above 1000 N·m/g. In some embodiments, the specific strength of the core material is between 50 N·m/g and 500 N·m/g in combination with a specific elastic modulus between 1 to 100 GPa·cm³/g, other suitable specific elastic moduli are: (1) above 1 GPa·cm³/g, (2) above 10 GPa·cm³/g, (3) above 100 GPa·cm³/g, or (4) above 1000 GPa·cm³/g.

[0050] Exemplary materials that are suitable for use in the barrel core include (without limitation) (1) iron and iron alloys/ferrous alloys, especially steels, e.g. 4140, 4150, 416R and reinforced iron materials like metal-matrix materials from iron based alloys; (2) nickel and nickel alloys, e.g. Inconel and reinforced nickel materials like metal-matrix materials from iron/ferrous alloy materials; (3) copper and copper alloys, especially in combination with zinc, tin, nickel and beryllium, commonly referred to as bronze, brass, copper-nickel, Gunmetal and beryllium bronze and reinforced copper materials like metal-matrix materials from the aforementioned copper-based materials; (4) cobalt, cobalt alloys and reinforced cobalt materials like metal-matrix materials; (5) chrome and chrome alloys and reinforced chrome materials like metal-matrix materials; (6) beryllium and beryllium alloys and reinforced beryllium materials like metal-matrix materials; (7) magnesium and magnesium alloys and reinforced magnesium materials like metal-matrix materials; (8) aluminum, aluminum alloys and reinforced aluminum materials like metal-matrix materials from aluminum based materials; (9) molybdenum and molybdenum alloys and reinforced molybdenum materials like metal-matrix materials from molybdenum based materials; (10) niobium and niobium alloys; (11) tantalum and tantalum alloys; (12) titanium and titanium alloys, e.g. different titanium grades and gold-titanium alloys; (13) tin and tin alloys; (14) tungsten and tungsten alloys; (15) osmium and osmium alloys; (16) zinc and zinc alloys; (17) zirconium and zirconium alloys; (18) hard metals; (19) metal carbides, like tungsten carbide; (20) metal bonded ceramics, so called Cermets; (21) sintered ceramics, both carbide and non-carbide ceramics; and (22) other metal-ceramics, e.g. metal or polymer infiltrated ceramics, in which both substituents can be both interconnecting and non-interconnecting/inter-permeating and non-inter-permeating.

[0051] As referenced herein, the term alloy is used to describe any combination, blend and/or mixture of mainly metallic materials and is not to be understood to follow the scientific definition of alloy. For example, the term is intended to include super alloys, base alloys, performance alloys, intermetallic phases, inter-permeating phases and metallic glasses as well as different material grades and reinforced materials. Some materials may or may not be part of one or several of the above-described materials and material classes and such groupings of materials should not be understood to be mutually exclusive. Additionally, in

some embodiments, the barrel core may include a functional coating. Examples of such coatings include hard coating that prevent scratching and improve abrasion resistance, and low friction coatings.

[0052] In some embodiments, as shown in FIGS. 4A-4E, the barrel sleeve may be selected from a variety of configurations that enhance the stiffness and other mechanical properties of the barrel. For example, in the embodiment of FIG. 4A, an illustrative cross-section of a gun barrel **300**, which is analogous to the gun barrel **102** of FIG. 1, includes a steel core **302** and an outer sleeve **316** formed from a matrix material. Voids or channels **304** are formed within the sleeve **316**, and may be formed to have cross-sections that appear as circles, parallelograms, arcuate segments, or any other suitable shape.

[0053] The embodiment of FIG. 4B is analogous in most respects to the embodiment of FIG. 4A. In the embodiment of FIG. 4B, however, the voids or channels **304** of the gun barrel **310** are populated with granules **306** of filler material, which may be a dampening material. Somewhat similarly, in the embodiment of FIG. 4C the voids or channels **304** of the gun barrel **320** are populated with an insert **308** of filler material, which may be a phase-change material (PCM) or a viscous damper material.

[0054] In the embodiment of FIG. 4D, the gun barrel **330** includes a core **302** and a sleeve **314**. The sleeve **314** includes radial fins **322**. The radial fins **322** may include enlarged sections **324**, which may be cylindrical sections as shown, at each distal end of the radial fins **322**. To enhance rigidity, the enlarged sections **324** may include a strengthening member **312**, which may be a strand or rod of high modulus material.

[0055] The embodiment of FIG. 4E is analogous in many respects to the embodiments of FIGS. 4A-4D, and includes many of the features described with respect to such embodiments. For example, the gun barrel **340** includes a plurality of channels or voids **304**. The voids **304** may be alternatingly populated with granules **306** and inserts **308**, as described above with respect to FIG. 4B and FIG. 4C, respectively. Analogous to the embodiment of FIG. 4D, a plurality of high modulus segments **318**, shown here as raised profiles, or ribs, may be spaced about the periphery of the gun barrel **340**. Like the enlarged sections **324** of FIG. 2D, the high modulus segments **318** may each include a strengthening member **312**.

[0056] In most embodiments, but referring again to FIG. 3C, for example, the sleeve surrounds **254c** the core **252c**, and is made from a light metal or metal-matrix material. Suitable sleeve materials include aluminum, scandium, francium, titanium, lithium, beryllium, magnesium, yttrium, calcium, potassium, sodium, barium, alloys of the foregoing, metallic glasses and intermetallic phases (herein further referred to simply as 'alloys') and metal-matrix materials based on these light metals and their alloys as matrix materials. For example, matrix materials may include aluminum, titanium, beryllium, or magnesium (or a combination thereof) and their alloys, together with fillers which are having at least the same or better thermal conductivity than the matrix material. For example, the filler material may have a thermal conductivity of more than 100 W/m·K. Such fillers may include carbon nanotubes, graphene, carbon fibers, copper, gold, silver, aluminum nitride, boron nitride, boron nitride nanotubes, beryllium oxide, beryllium, diamond or silicon carbide, most preferentially but not neces-

sarily with a high aspect ratio. As referenced herein, the “aspect ratio” denotes the ratio of average particle length divided by the average particle width. High aspect ratio filler particles are therefore elongated, fiber- or whisker-like with an aspect ratio that is generally above 20 (for a whisker-like particle), which means that the length is more than twenty times the diameter or width and much higher (100 or more) for a fiber-like particle.

[0057] In addition, in accordance with the illustrative embodiments, the sleeve material may have one or more of the following properties: (A) A linear thermal expansion coefficient of (1) between 0 and 30 ppm/K, (2) between 8 and 24 ppm/K, or (3) between 10 and 15 ppm/K; (B) a specific heat capacity of (1) more than 0.45 J/g·K, (2) between 0.7 and 2.0 J/g·K, or (3) above 2.0 J/g·K; (C) a thermal conductivity of between (1) 50 and 500 W/m·K, or (2) above 500 W/m·K; and (D) a specific tensile strength of (1) at least 80 N·m/g or (2) more than 150 N·m/g, see also Examples 1 and 2.

[0058] The foregoing configuration and combination of properties allows for an increased barrel thickness, or outer diameter, relative to a single-material barrel. Such increased barrel thickness (in addition to other factors) significantly stiffens the barrel and enhances performance without significantly increasing barrel weight. Further, the thermal expansion coefficients of the sleeve/sleeves 254c and the core 252c may be closely matched to reduce the risk of separation at increased temperatures, as detailed in Example 1.

[0059] The foregoing description of barrel configurations utilizes a combination of materials, design and joining techniques to provide numerous enhancements. As noted, the material used to form the sleeve 254c may have a higher thermal conductivity and specific heat capacity than that of the core 252c. The effect of such increased thermal conductivity and specific heat capacity is to more evenly distribute heat along the barrel 250c, which has the effect of reducing the risk of hot spots. In addition, the increased external surface area of the barrel 250c improves heat dissipation which, when coupled with the enhanced thermal conductivity of the sleeve 254c provides for more efficient cooling and corresponding delayed heating of the barrel 250c during firing. Heat dissipation may be further enhanced by altering the shape of the sleeve 254c, as described with regard to FIGS. 4A-4E.

[0060] In some embodiments, e.g., the embodiments of FIGS. 2B and 2C (but referencing FIG. 2C for brevity), the core 152c and sleeve 154c may have generally cylindrical shapes. For concentric barrel designs the stiffness S is calculated from the second moment of inertia I

$$I = \pi/4 \cdot (R^4 - r^4),$$

where R is the outer radius of the barrel and r is the radius of the bore. The stiffness S is calculated by multiplying the second moment of inertia I with the materials elastic modulus E

$$S = E \cdot I = K \cdot \pi/4 \cdot (R^4 - r^4).$$

[0061] In case of composite barrel there are at least three radii, r the radius of the bore 156c, R₁ the outer radius of the core 152c and R₂ the outer radius of the sleeve 154c, as well as two elastic moduli E₁ of the core 152c and E₂ of the sleeve 154c. The moments of inertia of the core I₁ and of the sleeve

I₂ add up to the total moment of inertia I_{total} and the total stiffness S_{total} is formed by the contributions of core 152c and sleeve 154c.

$$I_{total} = I_1 + I_2 = \pi/4 \cdot (R_1^4 - r^4) + \pi/4 \cdot (R_2^4 - R_1^4)$$

$$S_{total} = E_1 \cdot I_1 + E_2 \cdot I_2 = E_1 \cdot \pi/4 \cdot (R_1^4 - r^4) + E_2 \cdot \pi/4 \cdot (R_2^4 - R_1^4).$$

[0062] Examples based on different material combinations and resulting changes in the stiffness are given below in Example 3.

[0063] In other embodiments one or both of the core and sleeve may have a fluted, tapered, stepped, and/or ribbed outer surface (see, e.g., FIGS. 2D-2F), or a combination of these features. In an embodiment in which the core includes a fluted outer surface, however, the sleeve may include an inner surface that complements and surrounds the fluted outer surface of the core. To that end, the core may be generally cylindrical or may have any other suitable shape.

[0064] FIGS. 5A-5D show various embodiments of multi-material composite barrels. Generally, the variations shown lie in the extension of core in the sleeve as well as in the core thickness. In FIG. 5A, the barrel 400a includes a core 404a having a bore 402a. The core 404a is enclosed by a sleeve 406a that extends over the breach or chamber 408a at a first end and to the end of the barrel 400a at a second end. The core 404a also covers the whole length of the barrel 400a and also forms and contributes to the chamber 408a and has a macroscopic thickness of 1 mm or more.

[0065] The embodiments of FIGS. 5B-5D have many similar features, which may not be discussed for brevity. In FIG. 5B, the core 404b extends only partly (e.g., approximately half-way) into the length of the barrel 400b. The sleeve 406b therefore comprises a portion of the bore 402b in addition to rifling that forms the barrel 400b. In some embodiments, the barrel 400b is coated with a hard coating to reduce wear, e.g. being electroplated with chrome or diamond-like carbon (DLC) coatings produced by chemical vapor deposition (CVD). The thickness of the core 404b may vary. For example, the core 404b may have a greater thickness at the chamber 408a than in the bore 402b of the barrel 400b.

[0066] In the embodiment of FIG. 5C, the core 404c only extends partly (e.g., less than halfway) into the length of the barrel 400b. In such an embodiment, the core 404c has a minimal thickness and may be formed by, for example, applying a coating to the interior surface of the sleeve 406c. For example, the coating may be a diamond-like carbon (DLC) coating applied by chemical vapor deposition or electro plating with chrome to the interior surface of the sleeve 406c. Further, the core 404c may form only a shoulder 410c and not form the whole of the chamber 408c.

[0067] In the embodiment of FIG. 5D, the barrel 400d includes a core 404d having a reduced thickness, which may be formed as a coating of the sleeve 406d, such as those described above. The coating layer may change in thickness and material along the barrel. For example, a first coating material may be applied at the interior of the sleeve 406d to form a first portion 412d of the core 404d and a second coating material may be applied to form a second portion 414d of the core 404d. The first portion 412d and 414d may alternatively be thicker material layers such that the first portion 412d and second portion 414 may be joined with the sleeve 406d in accordance with any suitable fabrication method. In order to prevent gaps between the sleeve 406d and the first portion 412d and second portion 414d of the

core 404d, the surface of the bore 402d may be plated or coated to ensure a smooth transition over the different material sections.

[0068] In the embodiments of FIGS. 2-5, the barrel and the core may have identical or similar coefficients of thermal expansion (CTE, thereby facilitating direct joining of the barrel to the core. CTE is normally given in the unit parts per million per Kelvin (ppm/K). In order for sleeve and core to have thermal and mechanical integrity, it is desirable that there be little or no mismatch between the core and the barrel over the whole operating temperature range of the weapon. Former attempts to make bimetal composite barrels (e.g. from aluminum and steel) failed due to the fact that this criteria was not met, and the difference in thermal expansion coefficients for steel and aluminum is too large (12.4 ppm/K for 4140 steel and 23.6 ppm/K for 7075 Aluminum).

[0069] In some embodiments that feature light metals and metal-matrix sleeve materials, as disclosed herein, this is not the case. The thermal expansion coefficients of such materials differ by less than 50% from the core materials and in some cases by less than 25% (see Example 2). In such embodiments, two methods may be employed to ensure the mechanical and thermal integrity between the core and the sleeve over the operating temperature range of the weapon.

[0070] The first method involves using an interference fit, which may be achieved by shrink fitting, as described below. Here, interference implies that the core has a diameter that is larger than the opening in the sleeve so that the two parts interfere when assembled together. The extent of the desired amount of interference depends on the difference in thermal expansion coefficients between the parts to be joined, the temperature range through which the joint is to be maintained, and the localized geometry:

$$If = \Delta CTE \cdot \Delta T \cdot D,$$

where If is the Interference, ΔCTE is the difference in thermal expansion coefficients, ΔT is the temperature range in Kelvin and D is the local diameter of the core for where the interference is calculated.

[0071] The second method is to have an intermediate thin layer (coating or plating or foil) of another material between the core and the sleeve, wherein the thin layer has a higher thermal expansion coefficient than the sleeve material. In operation, the intermediate layer is confined between the sleeve and the core, and expands more rapidly during heating than each of the core material and the sleeve material. As such, the intermediate layer remains in compression between the core and the sleeve, thereby maintaining mechanical and thermal contact between the core and the sleeve. In such embodiments, the intermediate layer may be selected to have better thermal conductivity than the core material and similar or better thermal conductivity than the sleeve to mitigate possible insulating effects of the intermediate layer.

Damping and PCM Materials Geometries

[0072] In some embodiments, the material that forms the sleeve is a light-weight material (e.g., a material having a density of less than 5 g/cm³). Consistent with the embodiments described above, the sleeve may be configured such that an outer surface of the sleeve provides stiffness to the barrel [while the inner surface of the sleeve provides only minimal contact points to the core to provide structural support and resist deformation of the core and sleeve. To that

end, the sleeve may include voids or channels that provide for reduction of weight without compromising stiffness that may derive from the structure or geometry of the sleeve (see, e.g., FIGS. 2A-2F). In some embodiments, such voids or channels may be filled with granular or viscous filler materials.

[0073] Such filler materials may enhance heat transfer and provide dampening, which may reduce barrel whip during firing and barrel vibrations associated with firing. Examples of such filler materials include shot, granules and powders of sand, minerals, polymers, metals and other solids. Metals and heavy metal particles with a high density are also suitable. Exemplary materials include grains of depleted uranium, cobalt, tungsten, tungsten-carbide, gold, lead, copper, iron, steel, and so on. Other granular matter that is not flammable in the range of temperatures experienced by the weapon barrel may also be used. Potential damping viscous liquids that may be suitable include liquids that do not burn or boil over the range of operating temperatures of the barrel, including silicon oil, mercury, gallium, gallistan, and mineral oil. The material or material mixtures should also offer a sensible safety margin in case the gun is used outside the usual temperature range due to extraordinary circumstances like assault rifles in an extended firefight.

[0074] In further embodiments, dispersions and mixtures of solids and liquids are utilized as damping (filler) materials to further increase the viscosity and density of the filler material. Additionally, these embodiments allow the introduction of filler materials having thixotropic or rheopectic properties. Examples of such materials include silicon polymers and/or silicon oil reinforced with carbon nanotubes/exfoliated graphene platelets/talcum powder. The use of such materials allows, to an extent, smart responses of the barrel during operation. For example, the barrel may include a filler material that stiffens during a shot due to the shockwave of the gun-powder explosion and shot vibrations propagating through the barrel, thereby stiffening the barrel during the shot, reducing barrel whip, and increasing accuracy.

[0075] In some embodiments, the voids or channels may also or alternatively include a phase change material (PCM) that has a high heat of fusion (1) minimum of 10 kJ/kg and (2) between 10 and 200 kJ/kg or (3) above 200 kJ/kg. Suitable PCM materials have a first or second order phase change in the range of -40° F. (-40° C.) to 600° F. (300° C.) and/or undergo a hydration or dehydration reaction. The PCM may be selected to have a melting point that corresponds to a predetermined operating temperature or temperature range of the gun barrel, such that when the temperature of the gun barrel reaches the melting point of the PCM, the PCM will undergo a heat absorbing phase change (e.g. melting) and absorb a significant amount of thermal energy, thereby cooling and stabilizing the temperature of the gun barrel at the phase changing temperature of the PCM for a given number of shots. This is shown in Example 5 below for a composite barrel containing Rose's metal and gypsum as PCM materials.

[0076] Suitable metallic filler materials include alloys and eutectics which contain at least one of the following elements: Bi, Pb, Sn, Cd, In, Ga, Sb, Ag, Zn, Mg, Hg. Other suitable filler materials include (without limitation) Gallium-gallium antimony eutectic, gallium, Cerrowal eutectic, Bi—Cd—In eutectic, Cerrobend eutectics, Bi—Pb—In eutectic, Bi—In eutectic, Bi—Pb—Sn eutectic, Bi—Pb

eutectic, lead-bismuth-alloy, and bismuth-lead-eutectic-alloys, Rose's Metal, Newton's Metal, Field's Metal, Lipowitz's Metal, D'Arcet's Metal, D'Arcet's Alloy, Wood's Metal, Guthrie's Metal and Gallistan. The voids which contain the filler materials may be filled by coating or insertion.

[0077] Other non-metal PCM materials that may be similarly deployed as fillers include salts, salt-hydrates, paraffin, fatty acids, calcium sulfate (gypsum), organic-inorganic eutectics. These and the above-mentioned materials, blends and alloys may be suitable for the applications described herein for the purpose of latent heat storage and may also act as viscous dampers above their melting temperature. In some embodiments, the barrel profile may be shaped to enhance heat transfer and stiffness properties (see FIGS. 2D, 2E, 2F, 4D, and 4E). For example, the outer surface of the sleeve may be configured to include radial fins or channels that provide room for the addition of a thin but high modulus material insert to run along the barrel length between the fins or within the channels (see FIGS. 4D and 4E). Such high modulus material inserts, or 'rods', may also provide for increased barrel stiffness without the expense of high additional weight. The rods may also exhibit an elastic modulus of at least 100 GPa and in some embodiments, above 200 GPa. Examples of such high-modulus materials include titanium, beryllium, aluminum-glass-fiber composites, carbon, glass and basalt fibers and steel. It is further noted that PCM can be mixed with solids to improve thermal conductivity or to induce thixotropic or rheopectic properties in the PCM material, and to further increase multi-functionality.

Manufacturing Methods

[0078] The gun barrel disclosed herein may be formed using any suitable manufacturing process including, for example, extrusion and/or milling and joining by thermal shrink-fitting, casting, machining, over-molding, additive manufacturing (3-D printing), and combinations thereof.

Press Shrink Fitting

[0079] A method for forming a barrel 500 using a press-shrink-fit manufacturing technique is described with regard to FIGS. 6A and 6B. In accordance with the illustrative method, a sleeve blank 504 is provided and heated to a malleable state. In an embodiment, the sleeve blank 504 is formed from an MMC material. Following heating of the sleeve blank 504, a barrel core 502 is pressed into the bore of the sleeve blank 504. The sleeve blank 504 includes a first hollow region 506 that is sized and configured to receive the breach portion of the barrel core 502 and a second hollow region 508 to receive the remainder of the barrel core 502. In some embodiments, the press-fit operation is performed when the sleeve blank 504 is stabilized within a mold 510, which may include or be used with a guide block 512. Use of the mold 510 may prevent warping of the sleeve blank 504 during the joining process. After the barrel core 502 is pressed into the sleeve blank 504, the sleeve blank 504 is allowed to cool and contract, thereby forming a compressive joint between the sleeve blank 504 and barrel core 502.

[0080] A similar illustrative method is described with regard to FIGS. 7A-7C. This method is analogous to the method described with regard to FIGS. 6A and 6B, with the exception that the barrel core 602 is assisted in the press-fit operation by a tensile member 610 that is temporarily joined

(e.g., by external threading or internal threading that may be subsequently bored out) to the barrel core 602 to pull the barrel core 602 into the sleeve blank 604 as it is being press-fit into the hollow regions 606, 608 of the sleeve blank 604. The tensile member 610 may be a pull-rod, cable, or similar device.

[0081] In accordance with the illustrative method, a sleeve blank 604 is provided and heated to a malleable state. Following heating of the sleeve blank 604, a barrel core 602 is pressed into, and simultaneously pulled into (by tensile member 610), the bore of the sleeve blank 604. The sleeve blank 604 includes a first hollow region 606 that is sized and configured to receive the breach portion of the barrel core 602 and a second hollow region 608 to receive the remainder of the barrel core 602. In some embodiments, the press-fit operation is performed when the sleeve blank 604 is stabilized within a mold 612, which may include or be used with a guide block 614 and may extend over all or a portion of the barrel 600. Use of the mold 612 may prevent warping of the sleeve blank 604 during the joining process. After the barrel core 602 is pressed (and pulled) into the sleeve blank 604, the sleeve blank 604 is allowed to cool and contract, thereby forming a compressive joint between the sleeve blank 604 and barrel core 602.

[0082] In a preferred embodiment, the joining and manufacturing methods applied achieve a mechanical and thermally resilient joint between the sleeve and core. The joint is formed to maintain structural and thermal integrity over the full range of the weapon's operational temperature and mechanical stress. In some embodiments, an interference fit facilitates the achievement of the desired joint. The interference fit provides a strong, structural, mechanical and thermal load-bearing joint. As described above, the manufacturing process may be viewed as comprising the following steps: (a) cutting or machining the inner sleeve contour into a semi-finished sleeve or blank; (b) cutting or machining the core contour from semi-finished barrel or barrel blanks with the desired magnitude of interference; (c) heating the sleeve and cooling the core to expand the sleeve and to shrink the core; (d) sliding the parts onto/into each other; (e) allowing the parts to attain thermal equilibrium; and (f) finishing the barrel by machining final features like fluting, taper, boring, rifling, gas vents, cooling fins, striating, plating, tempering, engraving, etc.

[0083] Cooling the core and heating the sleeve provides the room necessary for the core to be inserted into a sleeve by thermally expanding and shrinking the parts respectively. Mating takes place by thermally equilibrating both parts, either by cooling or bringing them to the same temperature. The temperature difference during the first stage of joining is high enough to provide enough room for both parts. Heating can take place by continuously heating the sleeve in an oven by inductive, radiation or convective heating, either in a mold or free-standing. If a mold is used, the mold material will have a melting point that is higher than that of the sleeve material, or at least higher than the working temperature of the sleeve during the forming process. Suitable mold materials are graphite, steel, copper, and the like. Inductive heating in a graphite mold has proven to be a suitable method because it allows the fast application of thermal energy in the sleeve and keeps the sleeve thermally stable during the insertion of the core. Once inserted, the

core may act as a cooling rod that may cause cooling of the sleeve. Cooling may also be effected by exposure to liquid nitrogen.

[0084] An alternative embodiment of the manufacturing process, also resulting in an interference fit is a press-molding technique. The manufacturing process may be viewed as comprising the following steps: (a) cutting an inner sleeve contour into a semi-finished sleeve or blank; (b) cutting a core blank from semi-finished barrel or barrel blank with the desired interference (such that the core blank and sleeve blank may still have an interference fit, or very close to an interference fit, even when the sleeve blank is subsequently heated); (c) placing the hollowed-out sleeve into a mold; (d) heating both mold and sleeve to a temperature between the softening point and the melting point of the sleeve; (e) pressing the core/core blank into the softened sleeve; (f) allowing the parts to thermally equilibrate and/or to cool down to room temperature; and (g) finishing the barrel by machining final features like fluting, taper, gas vents, cooling fins, striating, plating, tempering, engraving etc.

[0085] As described above with regard to FIGS. 6A-6B and 7A-7C, pressing the core into the softened sleeve provides a fast method to join the parts, prevents bending, and also allows to surface structure the sleeve at the same time, so that a near net shape part is obtained. The pre-cut hollowed portion of the sleeve and the dimension of the mold in combination with the mass of the sleeve material allow predetermining the interference. Mating takes place by thermally equilibrating both parts, either by cooling or bringing them to the same temperature. Heating can take place by continuously heating the sleeve in an oven by inductive, radiation, or convective heating, either in a mold or free-standing. During the press operation, a plug can be inserted into the barrel core (assuming it is already bored) to prevent sleeve material from entering the bore. An alternative embodiment of this manufacturing process is 'pull-molding' (as described with regard to FIGS. 7A-7C). In such an embodiment, the barrel is not pressed into the softened sleeve but is pulled into it. Pulling has the advantage that the danger of bending during the mating is lower than during pushing. To that end, pulling may be done assistively or in lieu of pressing. For this operation, a threaded interface can be used to attach a pull-rod or rope to the core blank, and can be later cut off or be used to attach other accessories (e.g. a muzzle break or a flash hider). These manufacturing methods are suitable for medium and large scale production.

[0086] In accordance with another embodiment, injection molding can be used to manufacture the barrel and also provide an interference fit. The manufacturing process may be viewed as comprising the following steps: (a) cutting a core blank from a semi-finished barrel or a barrel blank with the desired interference; (b) placing the core blank in a mold which has a volume of sleeve at a temperature at which the sleeve material will be injected; (c) injecting the softened sleeve material into the mold; (d) allowing the parts to thermally equilibrate and/or to cool down to room temperature; and (e) finishing the barrel by machining final features like fluting, taper, gas vents, cooling fins, striating, plating, tempering, engraving, etc.

[0087] Injection molding a sleeve onto a core provides a fast method to join the parts, prevents bending, and also allows to surface structure the sleeve at the same time, so that a near net shape part may be obtained. The volume of

the mold and the injected sleeve material are important for the success of this method since they determine the quality of the joint of the finished barrel. Additionally, since metal-matrix materials may be used, phase separation of the filler and the matrix is prevented by either working the material in the softened state or the lower liquid state at which the viscosity is still high enough to prevent phase separation.

[0088] By way of example, thixotropic injection techniques, also called semi-solid casting, are suitable for this kind of manufacturing. In such an embodiment, formation of the mechanical and thermal load bearing joint takes place by thermally equilibrating both parts. To prevent high thermal stress during the injection, the core can be heated and, if already bored, further supported by an inserted rod that is configured to transmit heat to the core. This manufacturing method is also suitable for large scale production.

Press Shrink Fitting/Interference Fit

[0089] As referenced herein, press-shrink-fitting denotes a manufacturing technique that takes advantage of a property of metal-matrix materials that have a broad range below the melting point in which the materials are malleable. In accordance with an associated method, a sleeve blank, which may be hollowed out to accept a barrel core, can be placed in a mold and heated to a temperature at which it becomes malleable. A barrel core may also be pre-heated (and may or may not be already bored, chambered and rifled). The barrel core is then pressed into the sleeve by force, and both parts are then allowed to thermally equilibrate and to cool down. During cooling down, the sleeve contracts around the core and the core may expand into the sleeve, thereby forming a force-bearing fit that is similar to the aforementioned shrink fits. In such processes, the sleeve is sufficiently malleable to plastically deform and not to break when the core is inserted. It follows that it may also be possible to press a barrel core into a piece of soft malleable metal-matrix material without the necessity to pre-drill the sleeve. In accordance with this process, a mold around the sleeve keeps the material in place and prevents the metal-matrix material sleeve from bending. This process may further be used to pre-shape the sleeve during the joining process.

[0090] In some illustrative methods, the steel core is pulled instead of pushed into the sleeve, as described above with regard to FIGS. 7A-7C. In application of the foregoing process, the sleeve is drilled with a guide-hole that allows a pull-cable, rod, chain, or other tensile member to be inserted, which is used to pull the barrel core into the sleeve. An advantage of pulling is that the core aligns within the sleeve, guided by the guide-hole. Accordingly, the core is less prone to bending and misalignment during the joining process, compared to a simple press-fit operation.

Hipping

[0091] Hot isotactic pressing (HIP or hipping), is a manufacturing technique in which a component is subjected to both elevated temperature and isotactic gas pressure in a high pressure containment vessel. The pressure is applied from all directions and hence the term 'isotactic' is used. The method can be used to consolidate powders or reduce the porosity of already solid parts. This process can be used to hip the sleeve directly onto the barrel core by consolidating a metal-matrix powder or a semi-finished barrel blank

around either a core blank or an already chambered and rifled barrel blank. This technique provides for a strong and robust joint between the sleeve and the core.

[0092] Hot isotactic pressing processing parameters for (for example) an aluminum based MMC are in a temperature range around 500° C. and a pressure range of 45 to 100 MPa, at which they may be kept for 12 to 48 hours followed by an air cool. This prolonged heating period can affect the steel core's hardness and tensile strength since it is comparable to heat treatment/annealing. To that end, adverse effects can be addressed by using quenched steel core and by using the hiping both as a process to join core and sleeve and at the same time to temper or anneal the core and give the barrel the desired hardness and tensile properties.

[0093] Final processing may again include chambering and rifling of the core, drilling the gas port, threading the muzzle end and chamber, shaping and surface patterning the sleeve, polishing and plating etc.

Powder Consolidation

[0094] An alternative approach to manufacture the composite barrel is to surround the barrel core with an MMC tube, and to fill a gap between the tube and the exterior of the barrel core with an MMC powder. The powder may be identical in composition with the outer tube. The powder is then heated and sintered to consolidate the powder to the desired density and thereby create a force-bearing and thermal load-bearing conductive joint between the core and the outer tube. Whereas 'sintering/to sinter' is understood here as compacting and forming a solid mass of material by heat and/or pressure, without melting it to the point of liquefaction. An advantage of this manufacturing method is that it provides for little thermal stress on the structure as well as reduced applied pressure to achieve a high degree of consolidation of the powder.

[0095] In a powder consolidation process, the porosity of the sleeve can be adapted in a certain range and thereby mechanical and thermal properties can be tuned. For example, if there is a slight porosity maintained, then the vibration damping properties of the sleeve will be increased, while tensile strength and thermal conductivity are reduced. Here, a balance is struck between the different properties to achieve a combination that both allows the barrel to perform thermally and mechanically on the top of the barrel's operating limits. Since the powder's degree of compaction can easily be above 90% and above 95% of the theoretical bulk density it offers a fast and easy way to complete composite barrels with nearly identical properties to hot isotactically pressure joined composite barrel, without the need of exposing the steel core to high thermal stress. It also allows the use of different material combinations of fill-powder and outer tube, thereby giving more design liberties than monolithic sleeves described before. In order to ease manufacturing, pre-pressed, semi-finished filler-cores can be produced and then inserted into a void between the outer tube and the core, and then consolidated into the void. This is shown schematically in FIGS. 8A-9B.

[0096] In the illustrative process of FIGS. 8A and 8B, a barrel core 702 is surrounded by a thin walled MMC or other suitable material tube 704 that may ultimately form the external surface of a sleeve. The gap between the core and the tube is filled with a loose MMC powder 706, which is then consolidated by pressing and compacting the MMC powder 706 with a dye 708. FIG. 8B shows the powder

having been compacted to form a stable MMC filler layer 710 within the tube 704 to form an external sleeve.

[0097] Another illustrative process is shown in FIGS. 9A and 9B, and is analogous in most respects to the embodiment of FIGS. 8A and 8B. In this embodiment, a pre-shaped lightly consolidated green gap-core 806 is inserted into the gap between the tube 804 and core 802 in lieu of powder 706. The gap-core 806 is a generally cylindrical component formed from a material similar or identical to the powder that has already been compacted (e.g., 80% compacted relative to a completed sleeve) to the extent necessary to maintain a solid shape, but may still be further compactable. The gap-core 806 is subsequently compacted with a dye 808 to form a stable MMC filler layer 810 within the tube 804 to form an external sleeve. In some embodiments, a sintering step may be later performed to better solidify the filler layer (710 or 810).

Explosion Welding

[0098] Explosion welding is a solid state process in which the joining of a sleeve and core is accomplished by accelerating one of the components to extremely high velocities relative to each other. This acceleration may be achieved by an explosive compound, and the corresponding manufacturing process is capable of bonding two metals that may not be weldable by conventional means. In the explosion welding process, the constituent metals do not melt, but rather plasticize at their surfaces, bringing the materials into intimate contact and also creating a weld-bond.

[0099] The explosion welding technique is very suitable to produce simple geometries like plates and tubes. Accordingly, this technique is suited to join the sleeve on the core by imposing a hollowed out sleeve blank over the core, covering it with a suitable explosive and joining core and sleeve by igniting the explosive. Further processing may include but is not limited to chambering and rifling of the core, drilling the gas port, threading the muzzle end and chamber, shaping and surface patterning the sleeve, polishing and plating, etc.

Alternative Joining Methods

[0100] For the sake of completeness, there are several alternative manufacturing techniques that allow the construction of a barrel having an MMC sleeve and barrel core. Such manufacturing techniques may include but are not limited to:

[0101] Smiting: Similar to hammer forging, the sleeve can be forged onto the barrel core imposing a hollowed-out sleeve blank onto the barrel core, which then is drawn onto itself to decrease the diameter and to forge the sleeve tightly onto the barrel core. The barrel core and sleeve may or may not be heated to improve the joint and/or ease processing or to create a shrink or tighter fit after joining.

[0102] Conventional welding: The sleeve is made from one, two or more separate pieces that are arranged around the barrel core and then welded together, e.g. by steer-welding. For this process, the sleeve parts may or may not be heated to shrink after joining and to create a shrink or tighter fit.

[0103] Soldering: The sleeve may be made from one, two or more separate pieces that are arranged around the barrel core and then soldered together. The sleeve parts may or may not be soldered to the barrel core as well. For optimal

performance at high temperatures, a hard solder is preferential. The sleeve parts may be heated to facilitate shrinking after soldering to create a shrink or tighter fit. The sleeve may be made from one or several separate parts, which in turn can lock into/onto each other and/or the barrel core, and may be joined by a forging process.

[0104] Clamping: The sleeve is made from one, two or more separate pieces which are arranged around the barrel core and then clamped together and onto the core, e.g. by screws and screw holes integrated in the sleeve or other clamp/tightening devices, for this the sleeve parts may or may not be heated to shrink after joining and to create a shrink or tighter fit. The sleeve may or may not be made from one or several separate parts, which in turn can screw, clamp, click or join onto/into each other and/or the barrel core.

[0105] Screw connections: The easiest manufacturing technique to join sleeve and core is to equip both with the corresponding threads and simply screw the sleeve onto the core. This will result in a stable barrel but the voids in the threading may amount to weak points in terms of thermal conduction, structural stability, and structural integrity. Such weak points may effectively reduce the stiffness and thermal performance of a resulting barrel. Moreover, in order to provide sufficient pressure resistance, the core will have to have higher wall thicknesses than the above outlined designs. The sleeve may be made from one or several separate parts, which in turn can screw onto each other and/or the barrel core.

[0106] Cut Screw Connection: In an embodiment having screw connections, a steel core can be given a cutting thread and the sleeve an incomplete swallow thread. When the core is screwed into the sleeve, the core's threads cut into the sleeve, thereby reducing the disadvantages resulting from voids which may be associated with aforementioned screw connection. In such an embodiment, the sleeve may be made from one or several separate parts, which in turn can screw onto each other and/or the barrel core.

[0107] Adhesive Joining: The sleeve may be made from one, two, or more separate pieces, which are arranged around the barrel core and then glued together. The sleeve parts may or may not be glued to the barrel core as well. For optimal performance at high temperatures, a sleeve material of thermally conductive adhesive, such as (but not limited to) carbon nanotubes or exfoliated graphene platelets reinforced epoxy, is preferential. The sleeve parts may be heated to shrink after gluing and thereby create a shrink or tighter fit. The sleeve may or may not be made from one or several separate parts, which in turn can lock into/onto each other and/or the barrel core and may or may not be joined by an adhesive.

[0108] The features of the above-mentioned embodiments may be implemented in any suitable manner in conjunction with the features of other embodiments described herein. For example, it is possible to secure screw and screw-joints with adhesives. Loctite is the most common and commercially available representative of such adhesives. Such adhesive could be used to secure a screw-on-sleeve on the barrel core. Alternatively, a solder could be added to fill the voids in the thread and also hold the sleeve in place more permanently to prevent accidental loosening of the sleeve. Screws through the sleeve into the barrel core may serve the same function in clamp-on-embodiments.

EXAMPLES

Example 1

Metal-Matrix Composition and Properties to Match Barrel Cores

- [0109]** a. A common steel like 4150 has a CTE (Coefficient of Thermal Expansion) of 12.6 ppm/K, aluminum of 23.6 ppm/K. A 1 m piece of each steel and aluminum would have a mismatch in length of 11.0 microns after being heated by just one Kelvin. In order to match the CTE's aluminum has to be mixed with a second material with lower CTE, for example with
- [0110]** i. Silicon carbide with a CTE of 4 ppm/K, results in approximate fractions of aluminum 0.57 to 0.43SiC.
- [0111]** ii. Diamond with a CTE of 1.2 ppm/K, results in approximate fractions of aluminum 0.58 to 0.42 diamond.
- [0112]** b. A cobalt-chrome alloy like Stellite 21 has a CTE of 14.1 ppm/K, aluminum of 23.6 ppm/K. A 1 m piece of each Stellite and aluminum would have a mismatch in length of 9.5 microns after being heated by just one Kelvin. In order to match Stellite's CTE aluminum has to be mixed with a second material with lower CTE, for example with
- [0113]** i. Silicon carbide with a CTE of 4 ppm/K, results in approximate fractions of aluminum 0.52 to 0.48SiC.
- [0114]** ii. Diamond with a CTE of 1.2 ppm/K, results in approximate fractions of aluminum 0.58 to 0.42 diamond.
- [0115]** c. A common steel like 4150 has a CTE (Coefficient of Thermal Expansion) of 12.6 ppm/K, a beryllium alloy Beryllium S-200 of 14.5 ppm/K. A 1 m piece of each steel and beryllium would have a mismatch in length of 1.9 microns after being heated by just one Kelvin. In order to match 4150 steel's CTE beryllium has to be mixed with a second material with lower CTE, for example with
- [0116]** i. Silicon carbide with a CTE of 4 ppm/K, results in approximate fractions of beryllium 0.82 to 0.18SiC.
- [0117]** ii. Diamond with a CTE of 1.2 ppm/K, results in approximate fractions of beryllium 0.86 to 0.14 diamond.
- [0118]** To match a cobalt core with beryllium, the following amount would have to be added
- [0119]** i. Silicon carbide with a CTE of 4 ppm/K, results in approximate fractions of beryllium 0.96 to 0.04SiC.
- [0120]** ii. Diamond with a CTE of 1.2 ppm/K, results in approximate fractions of beryllium 0.97 to 0.03 diamond.

Example 2

Properties of Commercially Available MMCs

[0121] The table below shows properties of (1) 4150 steel, commonly used in barrels, (2) Stellite 21 a cobalt alloy, two commercially available metal-matrix materials (SupremEx 640 and 225, Materion Cooperation, Mayfield Heights, Ohio, USA, and an aluminum-diamond-composite by S. R.

Holloway disclosed in U.S. Pat. No. 6,482,248B1 ‘Aluminium Composite for Gun Barrels’.

	4150 Steel	Stellite 21	SupremEx 640	SupremEx 225	Aluminum-Diamond-Composite
Density [g/cm ³]	7.85	8.31	2.90	2.88	3.10
CTE [ppm/K]	12.6	14.1	13.4	15.5	4-5
Tensile Strength [MPa]	972	724	560	610	379
Specific Tensile Strength [N · m/g]	124	87	193	212	122

Example 3

Increased Stiffness and Weight Examples 7.62 mm Caliber

[0122] The table below shows a comparison of (a) physical properties of the steel barrels shown in FIGS. 10A and 10B in 7.62 mm caliber made from 4150/4140 steel with two diameters, commonly found in AR-style barrels, as shown in FIGS. 10A and 10B, to (b) corresponding MMC composite barrels with thick barrel core, in which the steel core is still capable of maintaining the pressure alone. Weight and specific heat capacity are given for 1 mm slices. As an exemplary MMC SupremEx 640, Materion LLC, was chosen.

FIG.	Mtl	Diam.		Area Momentum	Stiffness	Weight		Spec. Heat Cap.	Surface Area
		[mm]	[in]	[mm ⁴]	[N · m ²]	[g]	[oz]	[J/K]	[cm ²]
4140 Steel Barrel, 7.62 mm Caliber									
10A	4140 Steel	24.11	0.950	1.64E4	3.44E3	3.23	0.104	1.46	0.757
10B	4140 Steel	22.20	0.875	1.17E4	2.46E3	2.68	0.086	1.21	0.697
Composite Barrel, 4140 Steel Core, SupremEx 640 Sleeve, 7.62 mm Caliber									
10C	4140 Steel	17.77	0.70	0.47E4	0.99E3	1.59	0.051	0.72	—
	Suprem-Ex 640	30.46	1.20	3.73E4	5.22E3	1.39	0.045	1.11	0.757
	Combined	30.46	1.90	4.20E4	6.21E3	2.98	0.096	1.83	1.08
10.D	4140 Steel	17.77	0.70	0.47E3	0.99E3	1.59	0.051	0.72	—
	Suprem-Ex 640	25.40	1.00	1.17E4	2.17E3	0.75	0.024	0.60	0.798
	Combined	25.40	1.00	1.64E4	3.16E3	2.34	0.075	1.32	0.798

Example 4

PCM-Materials and E-T-Curves

[0123] In the graph of FIG. 11, calculated heat curves are shown for 64 cm (25 in) barrels in different configurations. The calculation is based on an assumed heat deposition of 3500 J per shot into a barrel, which corresponds to the kinetic energy of 7.62 mm round, assuming an efficiency of

1/3 for the heat engine. It is further assumed the PCM barrels have 8 holes of 20 cm length and 4 mm diameter drilled into the sleeve to accommodate different PCM materials, here Rose’s metal and gypsum. The base data for the different barrels are as follows:

	Weight [g]	Weight [oz]	Specific Heat [J/K]
Steel Barrel (see line 1101)	1683	59.37	760
MMC Barrel (see line 1102)	1593	56.19	871
MMC Barrel + Rose’s Metal (see line 1103)	1815	64.02	858
MMC Barrel + Gypsum (see line 1104)	1710	60.32	997

[0124] It can be seen in the graph shown as FIG. 11 that gypsum has a higher latent heat than Rose’s metal and can keep the barrel at temperature of 110° C. for more than 20 shots. Cooling effects are not taken into account.

[0125] The above-mentioned joining techniques, as well as HIP, might be different but share an inference fit to deliver structural integrity over the temperature range. The extent of the interference depends strongly on the parts dimensions, operation parameters, calibers and intended performance. In some embodiments, it is possible to vary the extent of the inference along the barrel axis and therefore the ‘tune’ the vibration properties of whole barrel. In the disclosed embodiments, tuning features such as tuning rings and bulges placed at selected locations along the barrel can be partly or fully replaced by sections with higher interference to create zones with higher stress and different vibration properties, thereby forming ‘virtual’ tuning rings or tuning zones.

[0126] It should be apparent from the foregoing that embodiments of an invention having significant advantages have been provided. While the embodiments are shown in only a few forms, the embodiments are not limited but are susceptible to various changes and modifications without departing from the spirit thereof.

What is claimed is:

1. A gun having a composite gun barrel, wherein the barrel comprises:

- an inner core; and at least one outer sleeve that surrounds the circumference of the core over a length of the core, the sleeve being joined to the core over such length.
2. The gun of claim 1, wherein the inner core comprises a material selected from the group consisting of a ferrous alloy, a non-ferrous alloy, a ceramic, a bonded ceramic or a cemented carbide.
3. The gun of claim 1, wherein the outer sleeve comprises a metal or metal-matrix composite material with a density of less than 5 g/cm³.
4. The gun of claim 3, wherein the metal-matrix composite material comprises a matrix material selected from the group consisting of aluminum, scandium, francium, titanium, lithium, beryllium, magnesium, yttrium, calcium, potassium, sodium, barium their alloys, metallic glasses and intermetallic phases, and wherein the metal-matrix composite material further comprises a filler material selected from the group consisting of carbon nanotubes, graphene, carbon fibers, copper, gold, silver, aluminum nitride, boron nitride, boron nitride nanotubes, beryllium oxide, beryllium, diamond and silicon carbide.
5. The gun of claim 1, wherein the sleeve comprises a star-shaped cross-section having a plurality of points separated by arcuate segments.
6. The gun of claim 1, wherein the barrel comprises a sleeve with annular surface structure.
7. The gun of claim 1, wherein the sleeve extends over a length of the barrel from the muzzle to the end of the breach.
8. The gun of claim 1, wherein the sleeve extends over a length of the barrel from the muzzle to the opening of the breach.
9. The gun of claim 1, wherein the sleeve extends over a length of the barrel from an end of the breach to a plane that is offset from the end of the muzzle such that the core protrudes from the sleeve at the muzzle.
10. The gun of claim 1, wherein the sleeve comprises a plurality of longitudinal voids spaced at regular angular intervals about the sleeve.
11. The gun of claim 10, wherein the voids comprise cylindrical voids, and wherein a filler material is disposed within the voids.
12. The gun of claim 10, wherein the voids comprise arcuate segments, wherein a filler material is disposed within the voids, and wherein the filler material comprises at least one of a viscous damping material and a phase change material.
13. The gun of claim 1, wherein the sleeve comprises a plurality of fins spaced at regular angular intervals about the circumference of the sleeve, each fin including a filler material disposed therein, the filler material being selected from the group consisting of a phase change material and a viscous damping material.
14. A method of manufacturing a gun barrel comprising an inner core and at least one outer sleeve that surrounds the circumference of the core over a length of the core, the sleeve being joined to the core over such length, the method comprising:
- providing the core and the sleeve, wherein an internal diameter of the sleeve is smaller than an external diameter of the core;
 - heating the sleeve to a first temperature that is greater than the temperature of the core such that the internal diameter of the sleeve is slightly less than the external diameter of the core at the first temperature;
 - pressing the core into the internal diameter of the sleeve; and
 - allowing the core and the sleeve to reach thermal equilibrium.
15. The method of claim 14, further comprising pulling the core into the internal diameter of the sleeve.
16. The method of claim 14, further comprising stabilizing the sleeve and core within a mold prior to pressing the core into the internal diameter of the sleeve.
17. The method of claim 14, further comprising applying an intermediate layer to an external surface of the core prior to pressing the core into the internal diameter of the sleeve.
18. The method of claim 14, further comprising applying an intermediate layer to an internal surface of the sleeve prior to pressing the core into the internal diameter of the sleeve.
19. The method of claim 14, wherein the core comprises an annular ridge, and wherein the sleeve comprises an internal annular groove that complements the annular ridge.
20. The method of claim 14, wherein pressing the core into the internal diameter of the sleeve comprises aligning the annular ridge of the core with the annular groove of the sleeve.
21. A method of manufacturing a gun barrel comprising an inner core and at least one outer sleeve that surrounds the circumference of the core over a length of the core, the sleeve being joined to the core over such length, the method comprising:
- providing the core and the sleeve, wherein an internal diameter of the sleeve is smaller than an external diameter of the core;
 - heating the sleeve to a first temperature that is greater than 250° C.; and
 - applying a pressure of at least 20 MPa to press the core into the internal diameter of the sleeve.

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