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(54) **FRAME FOR A CARTRIDGE FOR A PLASMA ARC CUTTING SYSTEM, METHOD OF COOLING
THE PLASMA ARC CUTTING SYSTEM AND METHOD OF MANUFACTURING THE FRAME**

(57) A frame for a replaceable, unitary consumables cartridge configured for installation into a plasma arc torch. The frame includes a hollow body adapted to receive a translatable contact start electrode. The body has an internal surface and an external surface and includes: a substantially cylindrical metallic core; an electrically insulative overmolded plastic casing at least substantially surrounding a circumference of a distal end of the substantially cylindrical metallic core; and a set of flow passages fluidly connecting the external surface of the hollow body and the internal surface of the hollow body, the flow passages offset to impart a swirling fluid flow pattern to a plasma gases passing therethrough.

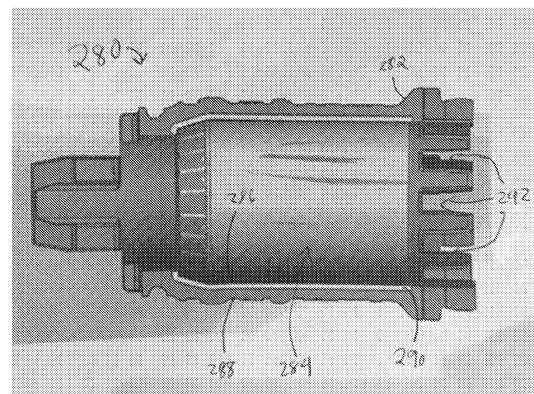


FIG. 2D

Description

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to U.S. Provisional Patent Application No. 62/756,996, filed November 7, 2018, entitled "Plasma Torch Cartridge", the entire content of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] The invention relates generally to the field of plasma arc cutting systems and processes. More specifically, the invention relates to methods and apparatuses for simplifying, optimizing and decreasing the time and cost of cutting through the use of improved consumable cartridges.

BACKGROUND

[0003] Plasma arc torches are widely used in the cutting and marking of materials. A plasma torch generally includes an arc emitter (e.g., an electrode), an arc constrictor or constricting member (e.g., a nozzle) having a central exit orifice mounted within a torch body, electrical connections, passages for cooling, and passages for arc control fluids (e.g., plasma gas). The torch produces a constricted ionized jet of a gas with high temperature and high momentum. Gases used in the torch can be non-reactive (e.g., argon or nitrogen) or reactive (e.g., oxygen or air). During operation, a pilot arc is first generated between the arc emitter (cathode) and the arc constrictor (anode). Generation of the pilot arc can be by means of a high frequency, high voltage signal coupled to a DC power supply and the torch or by means of any of a variety of contact starting methods.

[0004] Known consumables suffer from a host of drawbacks both before and during a cutting operation. Before a cutting operation, selecting and installing the correct set of consumables for a particular cutting task can be burdensome and time-consuming. During operation, current consumables encounter performance issues such as failing to effectively dissipate and conduct heat away from the torch and failing to maintain proper consumable alignment and spacing. Furthermore, current consumables include substantial amounts of expensive materials, such as Copper and/or Vespel™, which leads to significant manufacturing costs and inhibits their widespread commercialization, production and adoption. What is needed is a new and improved consumable platform that decreases manufacturing costs, increases system performance (e.g., heat conduction, component alignment, cut quality, consumable life, variability/versatility, etc.) and eases installation and use of consumables by end users.

SUMMARY OF THE INVENTION

[0005] The present invention provides one or more cost effective cartridge designs that reduce manufacturing costs, facilitate cartridge commercialization and production, improve installation and ease of use by end users, and increase system performance. In some embodiments, numerous traditional consumable components (e.g., swirl ring, nozzle, shield, retaining cap, and electrode components) are redesigned. In some embodiments new components (e.g., an electrode sleeve, a lock ring, and/or an interfacing insulator) are created. In some embodiments, a conventional swirl ring is replaced with a different feature within the torch body that imparts a swirl to a gas flow within the torch body (e.g., a swirl feature having flow holes built directly into a body of the nozzle). In some embodiments, a nozzle shield is electrically isolated from the nozzle (e.g., by using anodized aluminum and/or plastic).

The invention provides, inter alia, the subject matter of the following clauses:

1. A frame for a replaceable, unitary consumables cartridge configured for installation into a plasma arc torch, the frame comprising:

a hollow body adapted to receive a translatable contact start electrode, the body having an internal surface and an external surface, the body including:

a substantially cylindrical metallic core;
an electrically insulative overmolded plastic casing at least substantially surrounding a circumference of a distal end of the substantially cylindrical metallic core, and
a set of flow passages fluidly connecting the external surface of the hollow body and the internal surface of the hollow body, the flow passages offset to impart a swirling fluid flow pattern to a plasma gases passing therethrough.

2. The frame of clause 1 wherein the substantially cylindrical metallic core is formed by stamping.

3. The frame of clause 1 wherein the substantially cylindrical metallic core is made of brass.

4. The frame of clause 1 wherein the substantially cylindrical metallic core includes an anodized portion.

5. The frame of clause 1 wherein each flow passage in the set of flow passages is radially offset from the other flow passages.

6. The frame of clause 1 wherein the flow passages have a total cross-sectional area of about one square inch.

7. The frame of clause 1 wherein a first end of the frame is configured to connect to a nozzle.

8. The frame of clause 7 wherein the set of flow passages extends into a further component inseparably attached to a front of the nozzle. 5

9. A method of cooling a plasma arc torch, the method comprising:

providing a composite consumable having a frame defining a plurality of holes, the composite consumable having integrated components including an electrode, a nozzle and a shield, the holes fluidly connecting an external surface of the frame and an internal surface of the frame, the holes offset to impart a swirling fluid flow pattern to plasma gases passing therethrough; 10

installing the composite consumable in the plasma arc torch; and 20

flowing a cooling fluid through the plurality of holes, the cooling fluid forming a fluid flow pattern that cools at least one of the electrode, nozzle or shield, 25

wherein the frame is adapted to receive a translatable contact start electrode and includes (i) a substantially cylindrical metallic core; and (ii) an electrically insulative overmolded plastic casing at least substantially surrounding a circumference of a distal end of the substantially cylindrical metallic core. 30

10. The method of clause 9 wherein the substantially cylindrical metallic core is formed by stamping.

11. The method of clause 9 wherein the substantially cylindrical metallic core is made of brass. 40

12. The method of clause 9 wherein the substantially cylindrical metallic core includes an anodized portion. 45

13. The method of clause 9 wherein each hole in the plurality of holes is radially offset from the other holes.

14. The method of clause 9 wherein the holes have a total cross-sectional area of about one square inch. 50

15. The method of clause 9 wherein a first end of the frame is configured to connect to a shield via a shield insulator, the shield thermally coupled to the frame. 55

16. A method of manufacturing a replaceable, unitary consumables cartridge configured for installation in-

to a plasma arc torch, the method comprising:

providing a hollow body adapted to receive a translatable contact start electrode, the body having an internal surface and an external surface, the body including a substantially cylindrical metallic core;

overmolding an electrically insulative plastic casing on the hollow body, the electrically insulative plastic casing at least substantially surrounding a circumference of a distal end of the substantially cylindrical metallic core, and

providing a set of flow passages fluidly connecting the external surface of the hollow body and the internal surface of the hollow body, the flow passages offset to impart a swirling fluid flow pattern to a plasma gases passing therethrough.

[0006] In some embodiments, each cartridge comprises one or more of the following consumable components: a frame or body having one or more sections; an arc emitter (e.g., an electrode); an arc constrictor or arc constricting member (e.g., a nozzle); a feature to impart a swirl to a gas within the plasma torch (e.g., a swirl feature built into the nozzle, a swirl ring, or another swirl feature); a shield (e.g., a nozzle shield that is electrically isolated by the use of aluminum, anodized aluminum and/or a plastic material); an emitting element (e.g., a hafnium emitter); and/or an end cap. In some embodiments, a cartridge includes a substantially copper portion (e.g., a copper inner core) and a substantially non-copper portion (e.g., a non-copper portion external to the inner core). In some embodiments, a cartridge can be used on a hand-held plasma cutting system and/or a mechanized plasma cutting system. 35

[0007] In some embodiments, a cartridge has a resilient element, such as a spring electrode or a spring start mechanism affixed to an electrode, integrated directly into the cartridge and designed not to be separable or disassemblable from the cartridge. The resilient element can be in physical communication with the frame and/or can be configured to pass a pilot current from the frame to the arc emitter. The resilient element can bias the arc emitter in a direction along an axis of the resilient element, e.g., by imparting a separating force. In some embodiments, the separating force has a magnitude that is less than a magnitude of a coupling force holding the cartridge together. 40

[0008] In some embodiments, the cartridge has enhanced cooling and insulative capabilities, reduced manufacturing and material costs, and/or improved recyclability, durability and performance. In some embodiments, the cartridge provides consumable components in one integrated piece. In some embodiments, the cartridge enables a significantly reduced torch installation time (e.g., by a factor of 5-10); ensures that mating parts are 45

always chosen correctly for a given cutting task; improves heat dissipation and/or conduction capabilities; enables easier recognition of appropriate consumable components for a given cutting task; enhances consumable alignment and/or spacing; and/or reduces operator error. In some embodiments, heat is moved substantially away from the torch, but not so far as to heat or melt plastic components. In some embodiments, using a metal besides copper (e.g., in a region outside an inner core of copper components) helps move heat away from the torch. In some embodiments, the cartridge allows specific combinations of consumables to be pre-chosen for specific cutting tasks.

[0009] In some embodiments, the cartridge frame includes a strongly thermally conductive material, e.g., aluminum, copper, or another highly conductive metal. In some embodiments, the cartridge frame is formed by molding. In some embodiments, at least one of the first end of the cartridge frame or the second end of the frame includes a threaded region shaped to engage a complementary component. In some embodiments, the shield, the arc constrictor and the frame are thermally coupled. In some embodiments, an external surface of the frame is shaped to connect to a retaining cap. In some embodiments, the cartridge includes a shield insulator connected to the frame. In some embodiments, the shield insulator is press fit to the frame.

[0010] In some embodiments, a cartridge cap defines an aperture of the arc emitter and includes a fluid sealing surface disposed about a circumference of the arc emitter aperture. In some embodiments, the electrode comprises a spring. In some embodiments, the cartridge cap extends within a base region of the arc constricting member to a location near the set of swirl holes. In some embodiments, a base of the arc constricting member is formed by molding. In some embodiments, a retaining cap is connected to the cartridge body. In some embodiments, the retaining cap comprises a plastic. In some embodiments, the arc constricting member and the electrode are connected to the retaining cap via a base of the arc constricting member.

[0011] In some embodiments, a cartridge includes a shield connected to the cartridge body. In some embodiments, the shield is connected to the cartridge body via a shield insulator. In some embodiments, the shield insulator is press fit to at least one of the shield or a base of the arc constricting member. In some embodiments, the shield insulator is electrically insulative. In some embodiments, the shield insulator is thermally conductive. In some embodiments, the shield insulator includes anodized aluminum. In some embodiments, a sleeve is disposed about a portion of the electrode. In some embodiments, the sleeve includes an anodized layer formed to electrically isolate the electrode from a base of the arc constricting member. In some embodiments, the sleeve includes a set of flow surfaces configured to facilitate fluid flow within the plasma torch, e.g., to improve cooling.

[0012] In some embodiments, a cartridge (or consum-

able assembly) includes a seal disposed within the cap insert. In some embodiments, a cartridge includes a retaining cap directly connected to the gas flow diverter. In some embodiments, the retaining cap is formed of a plastic. In some embodiments, the arc constrictor and the emissive member are connected to the retaining cap via a swirl ring. In some embodiments, the shield insulator is press fit to at least one of the shield and the gas flow diverter. In some embodiments, the shield insulator is electrically insulative. In some embodiments, the shield insulator is thermally conductive. In some embodiments, the shield insulator includes anodized aluminum. In some embodiments, the shield has a heat capacity to current ratio of about 2 to about 4 W/m²·K-A. In some embodiments, the cartridge or consumable assembly includes a sleeve disposed about a portion of the emissive member. In some embodiments, the sleeve includes an anodized layer formed to electrically isolate the emissive member from a base of the arc constrictor. In some embodiments, the sleeve includes a set of flow surfaces.

[0013] In some embodiments, the cartridge is replaced as a unit. In some embodiments, a length of the emitting element can be adjusted to match the life of the nozzle, such that the cartridge parts reach the end of their useful lives at approximately the same time. In some embodiments, cut quality can be similar to that achieved using current consumables. In some embodiments, a cartridge type consumable assembly including a spring electrode disposed within a nozzle body and a sealing device disposed within a lock ring. The sealing device can be configured to connect to a plasma arc torch. The spring electrode can include a thumbtack or contact element that extends within the electrode body and is connected to a spring disposed between the contact element and the electrode body. In some embodiments, the electrode sleeves can have shaped (e.g., scooped) front ends to direct gas flow within the cartridge.

[0014] In one aspect, the invention features a replaceable cartridge for a plasma arc torch. The replaceable cartridge includes a cartridge body having a first section and a second section. The first and second sections are joined at an interface to form a substantially hollow chamber. The interface provides a coupling force that secures the first and second sections together. The cartridge also includes an arc constricting member located in the second section. The cartridge also includes an electrode included within the substantially hollow chamber. The cartridge also includes a contact start spring element affixed to the electrode. The spring element imparts a separating force that biases the electrode toward at least one of the first section or the second section of the body. The separating force has a magnitude that is less than a magnitude of the coupling force.

[0015] In some embodiments, a gas input moves the electrode and overcomes the separating force. In some embodiments, at least a portion of the electrode and the contact start spring element are irremovably disposed within the substantially hollow chamber. In some embod-

iments, a base of the arc constricting member is anodized. In some embodiments, the cartridge has a region with a thermal conductivity of between about 200-400 Watts per meter per degree Kelvin. In some embodiments, the shield has a heat capacity to current ratio of 2-4 W/m-°K-A. In some embodiments, the cartridge includes a cap insert connected to the second section of the cartridge body, the cap insert substantially orienting the electrode and retaining the electrode within the cartridge body.

[0016] In another aspect, the invention features a sealed cartridge unit for a plasma arc torch. The cartridge unit includes a substantially hollow frame including a first substantially hollow portion defining a first end and a second substantially hollow portion defining a second end. The cartridge unit includes an arc emitter located within the frame. The arc emitter is translatable relative to the frame. The cartridge includes an arc constrictor attached to the second end of the frame. The cartridge includes a resilient element in physical communication with the frame. The resilient element biases the arc emitter toward one of the first end or the second end to facilitate ignition at or near the arc emitter.

[0017] In some embodiments, a gas input moves the electrode and overcomes the separating force. In some embodiments, the frame includes an electrical insulator. In some embodiments, the frame includes at least one of a metal or a strongly thermally conductive material. In some embodiments, the frame is anodized. In some embodiments, the cartridge includes at least one set of flow holes, each flow hole in the set of flow holes radially offset from the other flow holes. In some embodiments, the flow holes have a total cross-sectional area of about one square inch. In some embodiments, the first end is configured to connect to a shield via a shield insulator, and the shield, the arc constrictor and the frame are thermally coupled. In some embodiments, the cartridge unit has a region with a thermal conductivity of between about 200-400 Watts per meter per degree Kelvin. In some embodiments, the cartridge includes a cartridge cap disposed in the second end of the frame, the cartridge cap shaped to contact the arc emitter and to retain the arc emitter within the frame.

[0018] In another aspect, the invention features a replaceable, unitary consumable assembly for a plasma arc torch. The consumable assembly includes a gas flow diverter, an arc constrictor in physical communication with the gas flow diverter, an emissive member disposed substantially within the gas flow diverter and the arc constrictor, and a resilient arc initiator disposed between the emissive member and at least one of the gas flow diverter or the arc constrictor. At least a portion of each of the gas flow diverter, the arc constrictor, the emissive member and the arc initiator are irremovably integrated within the consumable assembly.

[0019] In some embodiments, the emissive member includes an electrode and the arc starter includes a spring. In some embodiments, the gas flow diverter is

anodized. In some embodiments, the gas flow diverter includes a cap insert located substantially opposite the arc constrictor, the cap insert substantially orienting the emissive member and retaining the emissive member within the gas flow diverter. In some embodiments, a seal is disposed within the cap insert. In some embodiments, the consumable assembly includes a shield connected to the gas flow diverter. In some embodiments, the shield is connected to the gas flow diverter via a shield insulator.

[0020] In another aspect, the invention features a frame for a replaceable, unitary consumables cartridge configured for installation into a plasma arc torch. The frame includes a hollow body adapted to receive a translatable contact start electrode. The body has an internal surface and an external surface. The body includes a substantially cylindrical metallic core. The body also includes an electrically insulative overmolded plastic casing at least substantially surrounding a circumference of a distal end of the substantially cylindrical metallic core. The body also includes a set of flow passages fluidly connecting the external surface of the hollow body and the internal surface of the hollow body. The flow passages offset to impart a swirling fluid flow pattern to a plasma gases passing therethrough. In some embodiments, the substantially cylindrical metallic core is formed by stamping.

[0021] In some embodiments, the substantially cylindrical metallic core is formed by stamping. In some embodiments, the substantially cylindrical metallic core is made of brass. In some embodiments, the substantially cylindrical metallic core includes an anodized portion. In some embodiments, each flow passage in the set of flow passages is radially offset from the other flow passages. In some embodiments, the flow passages have a total cross-sectional area of about one square inch. In some embodiments, a first end of the frame is configured to be inseparably connected to a nozzle such that the nozzle, frame, and electrode are disposed as a single unit. In some embodiments, a first end of the frame is configured to connect to a shield via a shield insulator, the shield thermally coupled to the frame.

[0022] In another aspect, the invention features a method of cooling a plasma arc torch. The method includes providing a composite consumable having a frame defining a plurality of holes. The composite consumable has integrated components including an electrode, a nozzle and a shield. The holes fluidly connect an external surface of the frame and an internal surface of the frame. The holes are offset to impart a swirling fluid flow pattern to plasma gases passing therethrough. The method also includes installing the composite consumable in the plasma arc torch. The method also includes flowing a cooling fluid through the plurality of holes. The cooling fluid forms a fluid flow pattern that cools at least one of the electrode, nozzle or shield, thereby removing at least one watt of power from the plasma arc torch during operation. The frame is adapted to receive a translatable contact start electrode. The frame includes (i) a

substantially cylindrical metallic core; and/or (ii) an electrically insulative overmolded plastic casing at least substantially surrounding a circumference of a distal end of the substantially cylindrical metallic core.

[0023] In some embodiments, the substantially cylindrical metallic core is formed by stamping. In some embodiments, the substantially cylindrical metallic core is made of brass. In some embodiments, the substantially cylindrical metallic core includes an anodized portion. In some embodiments, each hole in the plurality of holes is radially offset from the other holes. In some embodiments, the holes have a total cross-sectional area of about one square inch. In some embodiments, a first end of the frame is configured to be inseparably connected to a nozzle such that the nozzle, frame, and electrode are disposed as a single unit. In some embodiments, a first end of the frame is configured to connect to a nozzle and/or a shield via a shield insulator, the shield thermally coupled to the frame. In some embodiments, the set of flow passages extends into a further component inseparably attached to a front of the nozzle. In some embodiments, the substantially cylindrical metallic core provides geometric stability, preventing the frame from changing shape, which could cause the electrode to cease and not slide, and/or cause the nozzle to fall off.

[0024] In another aspect, the invention features a method of manufacturing a replaceable, unitary consumable cartridge configured for installation into a plasma arc torch. The method includes providing a hollow body adapted to receive a translatable contact start electrode. The body has an internal surface and an external surface. The body includes a substantially cylindrical metallic core. The method includes overmolding an electrically insulative plastic casing on the hollow body. The electrically insulative plastic casing at least substantially surrounds a circumference of a distal end of the substantially cylindrical metallic core. The method also includes providing a set of flow passages fluidly connecting the external surface of the hollow body and the internal surface of the hollow body. The flow passages are offset to impart a swirling fluid flow pattern to a plasma gases passing therethrough.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] The foregoing discussion will be understood more readily from the following detailed description of the invention when taken in conjunction with the accompanying drawings.

Figure 1 is a cross-sectional schematic illustration of a cartridge for a plasma arc cutting system, according to an illustrative embodiment of the invention.

Figure 2A is an isometric illustration of a unitary cartridge for a plasma arc cutting system, according to an illustrative embodiment of the invention.

Figure 2B is a cross-sectional illustration of a unitary cartridge for a plasma arc cutting system, according to an illustrative embodiment of the invention.

Figure 2C is a cross-sectional illustration of a unitary cartridge for a plasma arc cutting system, according to an illustrative embodiment of the invention.

Figure 2D is a sectioned illustration of a plasma arc torch cartridge frame having an overmolded plastic casing, according to an illustrative embodiment of the invention.

Figure 3A is an isometric illustration of an inner cartridge assembly for a plasma arc torch, according to an illustrative embodiment of the invention.

Figure 3B is a cross-sectional illustration of an inner cartridge assembly for a plasma arc torch, according to an illustrative embodiment of the invention.

Figures 4A-4B are cross-sectional illustrations of consumable cartridges for a plasma arc cutting system, each cartridge having a nozzle, an electrode, a swirl ring, a resilient element and an end cap, according to illustrative embodiments of the invention.

Figure 5 is a cross-sectional illustration of a consumable cartridge for a plasma arc cutting system having a nozzle, an electrode, a swirl ring, a resilient element and an end cap, according to illustrative embodiments of the invention.

DETAILED DESCRIPTION OF THE DRAWINGS

[0026] Figure 1 is a cross-sectional schematic illustration of a cartridge 100 for a plasma arc cutting system, according to an illustrative embodiment of the invention. The cartridge 100 has a first end 104, a second end 108, and a substantially hollow frame 112 having a first section 112A toward the first end 104 and a second section 112B toward the second end 108. The cartridge 100 also includes an arc emitter 120, an arc constrictor 124, and a resilient element 128. The arc emitter 120 is located within the frame 112 and is translatable relative to the frame 112. As shown, the arc constrictor 124 forms a part of the frame 112 (e.g., at the second end 108, but in some embodiments can be attached to the frame 112). The resilient element 128 is in physical communication with the frame 112, e.g., is in direct physical communication with the first section 112A. In some embodiments, the resilient member 128 is a contact start spring element affixed to the arc emitter 120. The resilient element 128 can be configured to pass a pilot current from the frame 112 to the arc emitter 120. The resilient element 128 can bias the arc emitter 120 toward one of the first end 104 or the second end 108 to facilitate ignition at or near the arc emitter 120. The arc emitter 120 can be an electrode

and can include a highly emissive element 122 such as a hafnium insert.

[0027] The first section 112A and second section 112B are joined at an interface 132 to form a substantially hollow chamber. The interface 132 provides a coupling force (F_{coupling}) that secures the first section 112A and the second section 112B together. The resilient member 128 can impart a separating force ($F_{\text{separating}}$) that biases the arc emitter 120 toward at least one of the first section 112A or the second section 112B. The separating force can have a magnitude that is less than a magnitude of the coupling force. In some embodiments, the coupling force is provided at the interface 132 by at least one of a static frictional force, an adhesive force, or a normal force (e.g., a force countering a downward gravitational force) provided at a notch 136 of the interface 132. In some embodiments, the coupling force is stronger than is possible for a person to overcome by hand, either intentionally or inadvertently.

[0028] In some embodiments, the frame 112 includes at least one of a metal (e.g., aluminum) or other thermally conductive material. In some embodiments, the frame 112 is formed by molding. In some embodiments, the frame 112 is anodized (e.g., includes anodized aluminum, as set forth more fully below). In some embodiments, the frame 112 includes an electrical insulator, for example anodized aluminum and/or thermoplastics (e.g., PEEK, Torlon, Vespel, etc.). In some embodiments, at least one of the first end 104 or the second end 108 of the frame 112 includes a threaded region shaped to engage a complementary component. In some embodiments, the electrode 120 includes the resilient element 128 such as a spring.

[0029] In some embodiments, an external surface of the cartridge 100 is shaped to connect to, or mate with, a retaining cap or a cartridge cap (not shown). In some embodiments, the retaining cap is replaceable, threaded, and/or snap-on. The cartridge cap can be disposed about (e.g., can surround) the second end 108 of the frame 112. The cartridge cap can be shaped to contact the arc emitter 120 and to retain the arc emitter 120 within the frame 112. The cartridge cap can define an aperture of the arc emitter 120. The cartridge cap can include a fluid sealing surface disposed about a circumference of the aperture of the arc emitter 120. In some embodiments, the cartridge cap substantially orients the electrode 120 and retains the electrode 120 within the cartridge 100. In some embodiments, the cartridge cap includes a seal.

[0030] The cartridge 100 can be a "consumable" cartridge or assembly of consumable components, e.g., the cartridge 100 can be replaced as a unit after it reaches the end of its useful life. The cartridge 100 can be a sealed unit that is not intended to have individual component parts replaced. In some embodiments, individual components are irremovably disposed within or integrated into the cartridge 100. For example, at least a portion of the electrode 120 and the contact start spring element 128 can be irremovably disposed within the frame 112,

e.g., sealed within the frame 112 and/or not intended to be removed or replaced by an operator. In some embodiments, the cartridge 100 is a consumable component. In some embodiments, the components (e.g., frame 112 and arc constrictor 124) may be connected via press fits or other like means with tight tolerances and will degrade, fracture, or fail if separated.

[0031] Figure 2A is an isometric illustration of a unitary cartridge 200 for a plasma arc cutting system, according to an illustrative embodiment of the invention. Visible from the exterior are a plastic exterior section 204, a metallic exterior section 208, and a copper exterior section 212 (e.g., a nozzle shield). The plastic exterior section 204 and the metallic exterior section 208 are joined at a junction 206. In some embodiments, the junction 206 is included in or near a tapered region. In some embodiments, the plastic exterior section 204 is a retaining cap. In some embodiments, the metallic exterior section 208 is a shield insulator. In some embodiments, the metallic exterior section 208 is formed substantially of a material other than copper. In some embodiments, the copper exterior section 212 is formed of a pure or substantially pure copper or copper alloy. The components of the cartridge 200 are seen in more detail in Figure 2B, described below.

[0032] Figure 2B is a cross-sectional illustration of a unitary cartridge 200 for a plasma arc cutting system, according to an illustrative embodiment of the invention. In this view, additional elements of the cartridge 200 are visible, including a nozzle body 216, a nozzle orifice 218, an electrode 220 having an emitting element 222, an insulator sleeve 224 having an elongated portion 224A, a resilient element 226, and an electrode contact button 236 (e.g., made of brass). In the present invention, one or more of these elements can be redesigned to achieve one or more of the objectives set forth above.

[0033] For example, the nozzle body 216 can be formed from a conductive material (e.g., a highly conductive material such as aluminum) and can be attached to (e.g., can be in direct physical contact with) other parts of the cartridge 200. In some embodiments, the nozzle body 216 is in thermal communication with certain parts of the cartridge 200 (e.g., via thermal conduction) but electrically isolated from other parts. For example, the nozzle body 216 can function as a heat sink for the nozzle orifice 218 while remaining electrically isolated from the nozzle shield 212. Such a configuration can enhance cooling performance (for example, of the nozzle and the electrode) and reduce manufacturing costs by comparison to previously used materials (e.g., as Vespel™). In some embodiments, the cartridge has a region with a thermal conductivity of between about 200-400 Watts per meter per degree Kelvin (for example, aluminum may have a thermal conductivity of between 200-250 W/m-°K, while copper may have a thermal conductivity of between 350-400 W/m-°K). In some embodiments, the consumable cartridge has a heat capacity to current ratio of 2-4 W/m-°K-A.

[0034] In addition, the nozzle body 216 includes a set of inlet swirl holes 228 (e.g., swirl holes 228A and 228B). In some embodiments, the set of inlet swirl holes 228 includes five swirl holes, or optionally between three and ten swirl holes. The swirl holes 228 can be radially offset to impart a swirl flow (e.g., radial and tangential velocity components) to gases flowing therethrough (e.g., a shield gas, plasma gas, and/or a plenum gas). In this configuration, the nozzle body 216 provides the swirl function previously provided by a swirl ring, thus eliminating the need for a traditional swirl ring. In addition, in some embodiments the nozzle body 216 is formed via a molding process, thus eliminating the need for expensive and time-consuming drilling procedures to create the swirl holes. In some embodiments, the nozzle shield 212 includes an angle 232 that helps redirects fluid flow away from the plasma arc during operation.

[0035] Figure 2C is a cross-sectional illustration of a unitary cartridge 240 for a plasma arc cutting system, according to an illustrative embodiment of the invention. The unitary cartridge 240 can be similar in many respects to the cartridge 200 shown in Figure 2B but can differ in certain other respects. For example, the cartridge 240 utilizes a stamped torch interface 250 (e.g., a stamped pieces of copper) having a cross-sectional "T"-shape. The interface 250 can allow the electrode to slide more freely than in the Figure 2B configuration, which uses an electrode with a nipple feature that forms a mating surface with the spring. In Figure 2C, the cap and the nozzle body have been opened to ease manufacture and allow the electrode to slide freely into the nozzle body during cartridge assembly. The spring can then rest on the electrode, and the stamped torch interface 250 can use a small tab feature 252 to snap readily into the nozzle body, securing the electrode therein. Such a configuration avoids the need to press fit multiple pieces together (and, in turn, avoids the need to have to achieve tight tolerances between pieces) and/or the need to assemble different pieces of the torch from different directions. Using the cartridge 240, a manufacturer can simply slide the electrode into place in one step.

[0036] In addition, the cartridge 240 uses a molded, slotted swirl feature 266 to achieve the swirling function instead of using holes drilled in the nozzle body. In this configuration, during operation gas flows out of the slots 266 and into the plasma chamber to form the swirl gas about the plasma arc. During operation, gas may also flow through molded gas shield channel 254, further cooling the nozzle body. Slots 266 form a set of swirl holes once the nozzle body, nozzle orifice, and/or nozzle liner are connected. Gas delivered to the slots is conveyed from the torch through a chamber defined by an internal surface of the nozzle body and an external surface of the nozzle liner (which, in combination, form the swirl holes). Such a configuration eliminates post-process machining steps and the associated expenses. In addition, the cartridge 240 includes a radial swage connection 258 between the nozzle orifice and the nozzle body. The radial

swage connection 258 provides a robust connection interface to allow contact to be maintained between the nozzle orifice and the nozzle body, but also exposes significant surface area for heat to be conducted from the nozzle orifice to the nozzle body. Finally, in this embodiment, the electrode sleeve is removed and replaced with a more traditional heat exchanger.

[0037] Figure 2D is a sectioned illustration of a plasma arc torch cartridge frame 280 having an overmolded plastic casing 282, according to an illustrative embodiment of the invention. The frame 280 includes a hollow body 284 adapted to receive a translatable contact start electrode. The body 284 has an internal surface 286 and an external surface 288. The body 284 includes a substantially cylindrical metallic core 290, which can be formed by stamping. The body 284 also includes the electrically insulative overmolded plastic (such as a thermoset or thermoplastic) casing 282, which at least substantially surrounds a circumference of a distal end of the substantially cylindrical metallic core 290. In some embodiments, the body 284 also includes a set of flow passages 292 (e.g., at a distal end of the cartridge frame 280, as shown) fluidly connecting the external surface 288 and the internal surface 286. The flow passages 292 can be offset to impart a swirling fluid flow pattern to plasma gases passing therethrough. In one embodiment, the holes impart a swirling flow to a plasma gas entering into the plasma chamber into the cartridge, a portion of the plasma moving distally to generate a plasma arc and a portion of the gas moving proximally to cool the electrode. The flow passages 292 can be formed entirely within the plastic, e.g., by molding, and can enable crimping with another cartridge or torch component, e.g., the proximal end of a nozzle or shield (not shown). The crimped component can form part of the swirling flow passages 292.

[0038] In some embodiments, the cylindrical metallic core 290 helps to overcome certain thermal cycling and overheating issues with using molded plastics in a swirl ring. For example, plastics used in this context can exhibit a localized melting of the inner diameter, e.g., when the electrode is close to end of its life. At this point the electrode temperature can be higher than the melting point of the plastic used, causing it to melt and deform. Under these circumstances, the electrode in turn can be prevented from moving freely inside the swirl ring. In extreme cases, this malfunction can damage the torch (when the arc can be started but the electrode cannot move). In other failure modes, the nozzle may separate from the frame. As a solution, thermal plastic can be overmolded on a stamped brass piece to provide geometric stability such that the aforementioned melting and warping does not occur. The sleeve material can be a metal alloy and can be used with or without a second metal coating. In some embodiments, brass is used. Other metals that can be used include nickel-plated brass, copper, aluminum, steel, or other metals. Another benefit of overmolded plastic on a brass sleeve can be a decreased cost (e.g., \$1.30 as compared with about \$5 for Vespel). Such em-

bodiments can reduce or eliminate local melting in the inner diameter and can provide a reliable starting performance and robust torch.

[0039] Figure 3A is an isometric illustration of an inner cartridge assembly 300 for a plasma arc torch, according to an illustrative embodiment of the invention. Visible from the exterior are a shield 304 having vent holes 306 (e.g., holes 306A-D as shown), a nozzle body 308 having flow holes or inlet swirl holes 312 (e.g., holes 312A, 312B as shown in figure 3A), a front insulator (or shield insulator) 314, and a rear insulator (or lock ring) 316. These and additional elements are described more fully in conjunction with the cross-sectional view shown in Figure 3B below.

[0040] Figure 3B is a cross-sectional illustration of the inner cartridge assembly 300 of Figure 3A, according to an illustrative embodiment of the invention. In this view, several additional components of the inner cartridge assembly 300 are visible, including an electrode 320 having an emitting element 322, an arc constrictor or nozzle orifice 324, shield flow holes 328 (e.g., flow holes 328A-B as shown) directed toward the nozzle orifice 324, an insulator sleeve 332, and a cooling gas flow channel 336. In this embodiment, the nozzle body 308 functions as the cartridge frame to which other parts attach.

[0041] A number of features of the inner cartridge assembly 300 can enhance its cooling capabilities. First, the nozzle body 308 can be made of aluminum, which can enhance heat conduction over previous materials and configurations as described above. Second, the nozzle orifice 324 can be made of copper and can be pressed onto the nozzle body 308. In such embodiments, the nozzle body 308 can serve as a heat sink for the copper nozzle orifice 324. Third, improved gas flow surfaces, can assist in cooling, e.g., with shield gas flowing forward through holes 328A, 328B just outside of the press area. A press fit arrangement can also provide improved thermal conduction paths between torch parts as a result of tight tolerances between the surfaces of the parts. In some embodiments, the press fit arrangement includes an interference fit and/or a tabbed or interlocking fit having one or more step-like features. In addition, the small size of the press fit design has the additional advantages of reducing manufacturing and/or material costs and simplifying manufacture and assembly of the components (e.g., by having fewer parts).

[0042] The nozzle shield 304 can also be made of copper and can be pressed onto an anodized aluminum insulator 314 at a surface 305A. This assembly can then be pressed onto the nozzle body 308 at a press fit surface 305B. In such embodiments, the shield insulator 314 connects the nozzle body 308 to the shield 304. In some embodiments, the shield insulator 314 is press fit to the nozzle body 308. In some embodiments, the shield insulator 314 is an electrically insulative ring and/or includes a set of press-fit surfaces 305A, 305B that connect the shield 304 and the nozzle body 308. The shield insulator 314 can connect the nozzle body 308 to the shield 304

such that the nozzle body 308 and the shield 304 are electrically insulated from one another while still transferring thermal energy to one another. In some embodiments, using a two-piece shield insulator can increase (e.g., double) electrical insulation abilities as a result of increasing contact surfaces.

[0043] The nozzle shield 304 can be considerably smaller than previous shields, allowing for efficient manufacture and assembly of components, improved durability, and greater assurances of proper orientation of cartridge parts relative to one another. By way of example, for a 45-amp system, a prior art stock shield might have a diameter of about one inch and a mass of about 0.04 pounds, whereas a cartridge shield in accordance with the current invention can have a diameter of about 0.5 inches with a mass of less than 0.01 pounds (e.g., about 0.007 pounds). For a 105-amp system, a prior art stock shield might have a diameter of about one inch with a mass of about 0.05 pounds, whereas a cartridge shield in accordance with the current invention can have a diameter of about a half inch with a mass of about 0.01 pounds (e.g., 0.013 pounds).

[0044] The smaller size configuration can carry significant advantages. First, components having a reduced mass have a reduced heat capacity, which allows the components to be rapidly cooled during post-flow and/or allows more heat to be transferred to the cooling gas during operation. Second, a smaller shield can attain comparatively higher temperatures during operation and can transfer more heat to the cooling gas. In some embodiments, the nozzle shield 304 is exposed to a cold gas entering the shield area, e.g., via shield flow holes 328, which can further reduce the temperature. The flow holes 328 can each have a total cross sectional area of at least about one square inch.

[0045] In some embodiments, the electrode 320 includes a base made of copper. In some embodiments, the electrode 320 base has a small diameter with a pressed-on insulator sleeve 332 made of anodized aluminum and/or plastic used for electrical isolation. In some embodiments, a cooling gas flow channel or gap 336 exists between the insulator sleeve 332 and the nozzle body 308. In some embodiments, a cool gas flows in the gap 336. In some embodiments, a "dumbbell" configuration 340 defined by two end contacts 340A, 340B is used, which can reduce or minimize contact area between the nozzle body 308 and the insulator sleeve 332. Such a configuration can reduce friction between parts.

[0046] In some embodiments, the sleeve 332 contacts the electrode 320, which can be part of a separate current path from the nozzle body 308 and/or a different portion of the current path from the nozzle body 308. In some embodiments, the electrode 320 and the nozzle body 308 can be electrically separated by a gap to create the arc and/or to ensure proper orientation of the parts in the torch. In such embodiments, the nozzle 308 and the electrode 320 can be in physical contact between the sleeve 332 and the nozzle body 308. In such embodiments, in-

ulative layers are needed in this region so that current is able to pass through the emitting element 322.

[0047] In some embodiments, a wall of the nozzle body 342 near which the electrode 320 moves can stay comparatively cool during operation as gas flow passes both on the inside of the nozzle body 308 and directly across an exterior surface 344 of the nozzle 324. The material choice (e.g., aluminum or another metal) for the nozzle body 342 design provides for a better conduction path and heat sink ability as compared with previous materials such as Vespel™. Such factors assist in cooling the electrode isolation piece and allow the electrode to function even after a deep pit is formed in the emitting element from electrode use.

[0048] In some embodiments, a lock ring 316 (or isolation ring) forms an interface 346 between the cartridge 300 and the torch. In some embodiments, the lock ring 316 can be made of anodized aluminum. The lock ring 316 can be pressed into the nozzle body to "trap" the moveable electrode 320. The lock ring 316 can contain the components within the cartridge 300 and electrically isolate the torch. In some embodiments, the lock ring 316 is replaced by heat shrinking or gluing. In some embodiments, the lock ring 316 is shaped to orient the cartridge 300 (e.g., axially), to optimize gas flow, to enable electrical connection to the cathode, and/or to provide electrical isolation.

[0049] In various embodiments described herein, the cartridges or consumable assemblies are about 3.5 inches in length and 1.1 inches in diameter. In some embodiments, the retaining cap is considered part of the torch, e.g., not a consumable component. In such configurations, machining steps can be minimized, with no machining necessary after assembly (as compared to some torch assemblies that require a final machining step to achieve functional axiality of the cartridge). In some embodiments, the reduction in swirl holes can minimize drilling operations compared to prior art swirl rings. In some embodiments, replacing Vespel™ with aluminum can significantly reduce manufacturing costs of the cartridge. In some embodiments, copper is used only in certain locations in the electrode, nozzle, and/or orifice, which can reduce manufacturing costs by reducing the use of this expensive material. For example, copper can be concentrated primarily in an inner core or region. While copper can be desirable for its thermal and electrical properties, it is also more expensive than other materials, and so designs that minimize its usage are sought.

[0050] Figures 4A-4B and 5 are cross-sectional illustrations of consumable cartridges for a plasma arc cutting system, each cartridge having a nozzle, an electrode, a swirl ring, a resilient element and an end cap, according to illustrative embodiments of the invention. Figure 4A shows an exemplary cartridge design 400. As shown, the cartridge 400 includes a swirl ring 402, an end cap 406, a nozzle 408 and an electrode 404. The electrode 404 can be a spring-forward electrode for a contact start plasma arc torch, where a resilient element 412 (e.g., a

spring) exerts a separating force on the distal end of the electrode 404 to bias the electrode 404 away from the end cap 406 and toward the nozzle 408. The resilient element 412 can also be a part of the cartridge 400. The cartridge 400 can include a starting mechanism for contact starting a plasma arc torch upon assembly into the torch.

[0051] The swirl ring 402 can extend substantially over the length of the electrode 404 along a longitudinal axis 410 of the electrode 404. In some embodiments, the swirl ring 402 is manufactured through injection molding of high-temperature thermoplastics (e.g., PAI, PEI, PTFE, PEEK, PEKPEKK, etc). Use of thermoplastics to manufacture swirl rings can reduce cartridge cost in comparison to Vespel™, which is a material that has been used to manufacture swirl rings, but is comparatively more expensive. It is known that thermoplastics have operating temperatures that are lower than Vespel™ (a thermoset), which can impact the integrity of swirl rings and electrode life. However, the cartridge designs of the present technology, which can incorporate swirl rings made from thermoplastics resins having various fortifying additives that provide the desired thermal resistance and/or thermal conductivity (e.g., glass fibers, minerals, boron nitride (BN), and/or Cubic BN), have resolved the high temperature performance issues, thus enabling the effective use of thermoplastics in these cartridges. This is achieved since (1) thermoplastics have a sufficiently high-temperature resistance and (2) a cartridge design that properly incorporates thermoplastics can avoid exposure of the thermoplastics to excessive temperatures during operation. In addition, when an electrode experiences an end-of-life event, which is also the end of life of the cartridge, the simultaneous melting of the plastic material is not problematic.

[0052] The end cap 406 can be made of a conductive material, such as copper. The end cap 406 can be inexpensively formed via stamping from a material blank and can be irremovably inserted, press fit or over molded onto the cartridge 400. The end cap 406 is configured to contain the resilient element 412 within the cartridge 400 and compress the resilient element 412 against the distal end of the electrode 404 such that the resilient element 412 exerts a separating force on the distal end of the electrode 404 to bias the electrode 404 toward the nozzle 408. In some embodiments, end cap 406 may be shaped to matingly engage a patterned torch head and/or may include a set of fluid flow holes formed therethrough.

[0053] In some embodiments, an unreleasable snap-fit interface 414 is formed between the swirl ring 402 and the nozzle 408 to join the two consumable components together as a part of the cartridge 400. In addition, a second snap-fit interface 416 can be formed between the swirl ring 402 and the end cap 406 to join the two consumable components together as a part of the cartridge 400. Other manufacturing and assembly options are available and viable. For example, the swirl ring 402 can be over-molded onto the end cap 406. The end cap 406

can also be capsulated by the swirl ring 402 and the resilient element 412 (e.g., a spring), where the end cap 406 can move within the cartridge 400.

[0054] Figure 4B shows another exemplary cartridge design 450. As shown, the cartridge 450 includes a swirl ring 452, an end cap 456, a nozzle 458 and an electrode 454. In some embodiments, the cartridge 450 also includes a resilient element 462 that functions similarly as the resilient element 412 of FIG. 4A. The cartridges of Figures 4A and 4B have different electrodes (e.g., different sizes of heat exchanger flanges, circumferential flange for uniform flow), different nozzles (e.g., different swirl ring attachment), and different swirl rings (e.g., different swirl holes and attachment). In the cartridge design 450 of Figure 4B, an interface 464 is formed as the swirl ring 452 is inserted into position in relation to the nozzle 458. Another interface 466 can be formed between the swirl ring 452 and the end cap 456.

[0055] Figure 5 shows another exemplary cartridge design 500. As shown, the cartridge 500 includes a swirl ring 502, a sleeve 514, an end cap 506, a nozzle 508 and an electrode 504. In some embodiments, the cartridge 500 also includes a resilient element 512 that functions similarly as the resilient element 512 of Figure 4A. The sleeve 514 and/or end cap 506 can be made from a conductive material (e.g., copper) using a stamping method. The sleeve 514 can be press fit or over molded onto the cartridge 500. The end cap 506 can be a part of the sleeve 514. Therefore, the sleeve 514 and the end cap 506 can be constructed as a single component piece.

[0056] As shown, the swirl ring 502 can be relatively short in comparison to the swirl ring 402 such that the swirl ring 502 only extends along a portion of the length of the electrode 504 in the longitudinal axis 510. Similar to the swirl ring 402, the swirl ring 502 can be manufactured through injection molding of high-temperature thermoplastics (e.g., Torlon™). A snap-fit interface 520 can be formed between the swirl ring 502 and the nozzle 508 to join the two consumable components together as a part of the cartridge 500. Another snap-fit interface 518 can be formed between the swirl ring 502 and the sleeve 514 to join the two consumable components together as a part of the cartridge 500. Alternatively, the swirl ring 502 can be over-molded onto the sleeve 514.

[0057] There are many benefits associated with using a cartridge in a plasma arc torch. First, such a design promotes ease of use through quick change capabilities, short setup time and ease of consumable selection for an end user. It also provides consistent cut performance because a suite of consumables are changed at once when the cartridge is changed. In contrast, variation in performance is introduced when components are changed individually at different times. For example, long term re-use of the same swirl ring can cause dimensional alteration after each blowout, thereby altering the performance quality even if all other components are changed regularly. In addition, since the manufacturing and/or installation cost of a cartridge is lower than the

combined cost of a set of consumables, there is a lower cost associated with per cartridge change than per change of a set of consumables. Furthermore, different cartridges can be designed to optimize torch operation with respect to different applications, such as marking, cutting, maintaining long life, etc.

[0058] While the invention has been particularly shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the following claims.

Claims

1. A frame for a cartridge that can be replaced as a unit, the cartridge configured for installation into a plasma arc torch, the frame comprising:
a hollow body adapted to receive a translatable contact start electrode, the body having an internal surface and an external surface, the body including:

a substantially cylindrical metallic core;
an electrically insulative casing at least substantially surrounding a circumference of a distal end of the substantially cylindrical metallic core, and
a set of flow passages fluidly connecting the external surface of the hollow body and the internal surface of the hollow body, wherein each flow passage in the set of flow passages is radially offset from the other flow passages to impart a swirling fluid flow pattern to a plasma gas passing therethrough.

2. The frame of claim 1 wherein the substantially cylindrical metallic core is formed by stamping.
3. The frame of claim 1 wherein the substantially cylindrical metallic core is made of brass.
4. The frame of claim 1 wherein the substantially cylindrical metallic core includes an anodized portion.
5. The frame of claim 1 wherein the flow passages have a total cross-sectional area of about one square inch.
6. The frame of claim 1 wherein the frame is configured to connect to a torch component.
7. The frame of claim 6 wherein any one or more of the following applies:

a) the frame is configured to connect to the torch component via an unreleasable snap-fit interface;
b) a first end of the frame is configured to connect to the torch component via an unreleasable

- snap-fit interface;
- c) the frame is configured to be inseparably connected to the torch component;
- d) a first end of the frame is configured to be inseparably connected to the torch component; 5
- e) the torch component is a nozzle or a shield; or
- f) the frame is configured to connect the body of the frame to a torch component.
8. The frame of claim 6 wherein the set of flow passages extends into a further component inseparably attached to a front of the nozzle. 10
9. A method of cooling a plasma arc torch, the method comprising: 15
- providing a cartridge comprising the frame of claim 1, the cartridge having integrated components including the electrode, a nozzle and a shield; 20
- installing the cartridge in the plasma arc torch; and
- flowing a cooling fluid through the plurality of passages, the cooling fluid forming a fluid flow pattern that cools at least one of the electrode, 25
- nozzle or shield.
10. The method of claim 9 wherein
- a) the substantially cylindrical metallic core is formed by stamping; or 30
- b) the substantially cylindrical metallic core is made of brass.
11. The method of claim 9 wherein the substantially cylindrical metallic core includes an anodized portion. 35
12. The method of claim 9 wherein the holes have a total cross-sectional area of about one square inch. 40
13. The method of claim 9 wherein a first end of the frame is configured to connect to the shield via a shield insulator, the shield thermally coupled to the frame.
14. A method of manufacturing the frame of claim 1, the method comprising: 45
- providing a hollow body adapted to receive a translatable contact start electrode, the body having an internal surface and an external surface, the body including a substantially cylindrical metallic core; 50
- providing an electrically insulative plastic casing on the hollow body, the electrically insulative plastic casing at least substantially surrounding a circumference of a distal end of the substantially cylindrical metallic core, and 55
- providing a set of flow passages fluidly connect-

ing the external surface of the hollow body and the internal surface of the hollow body, wherein each flow passage in the set of flow passages is radially offset from the other flow passages to impart a swirling fluid flow pattern to a plasma gas passing therethrough.

15. A composite consumable having a frame defining a plurality of holes, the composite consumable having integrated components including an electrode, a nozzle and a shield, wherein the holes fluidly connect an external surface of the frame and an internal surface of the frame; the holes are offset to impart a swirling fluid flow pattern to plasma gases passing therethrough; the frame is adapted to receive a translatable contact start electrode; and the frame includes (i) a substantially cylindrical metallic core; and/or (ii) an electrically insulative overmolded plastic casing at least substantially surrounding a circumference of a distal end of the substantially cylindrical metallic core.

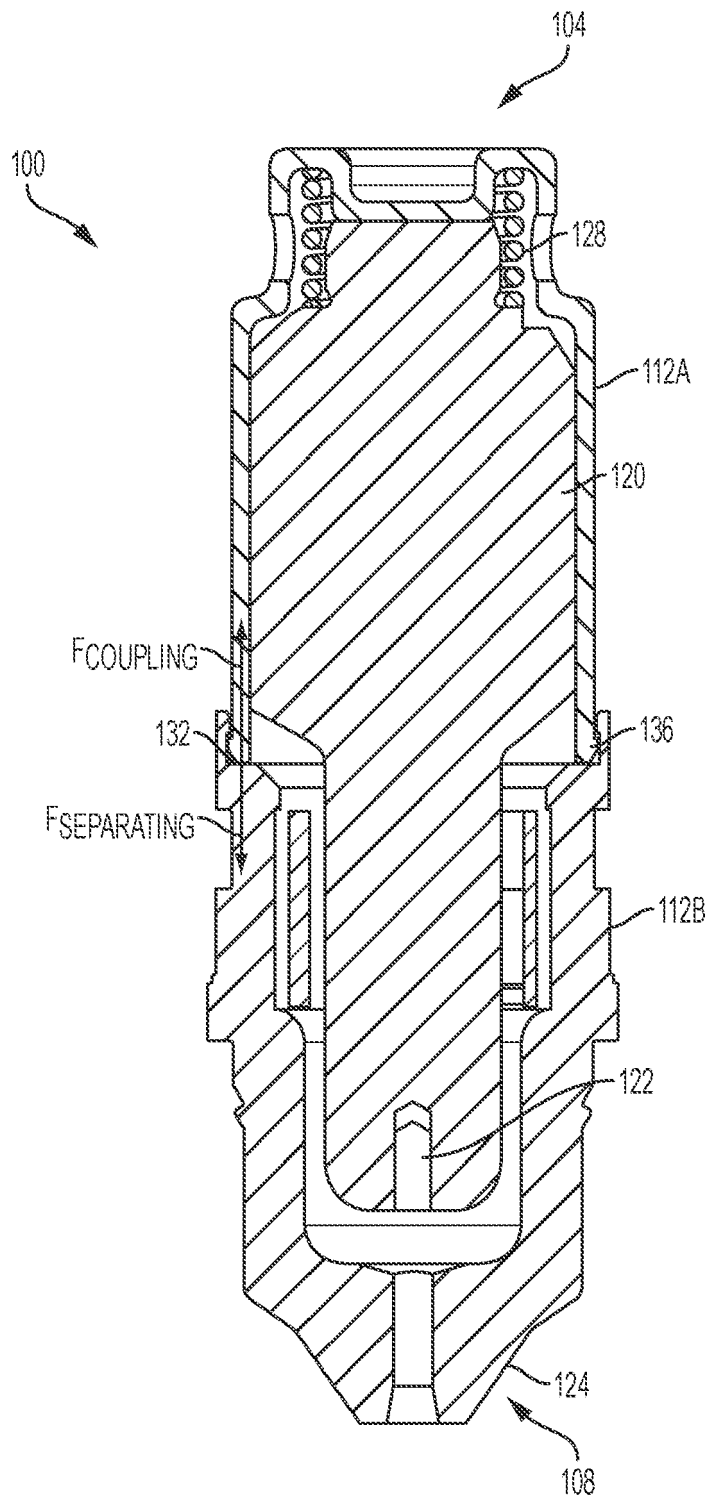


FIG. 1

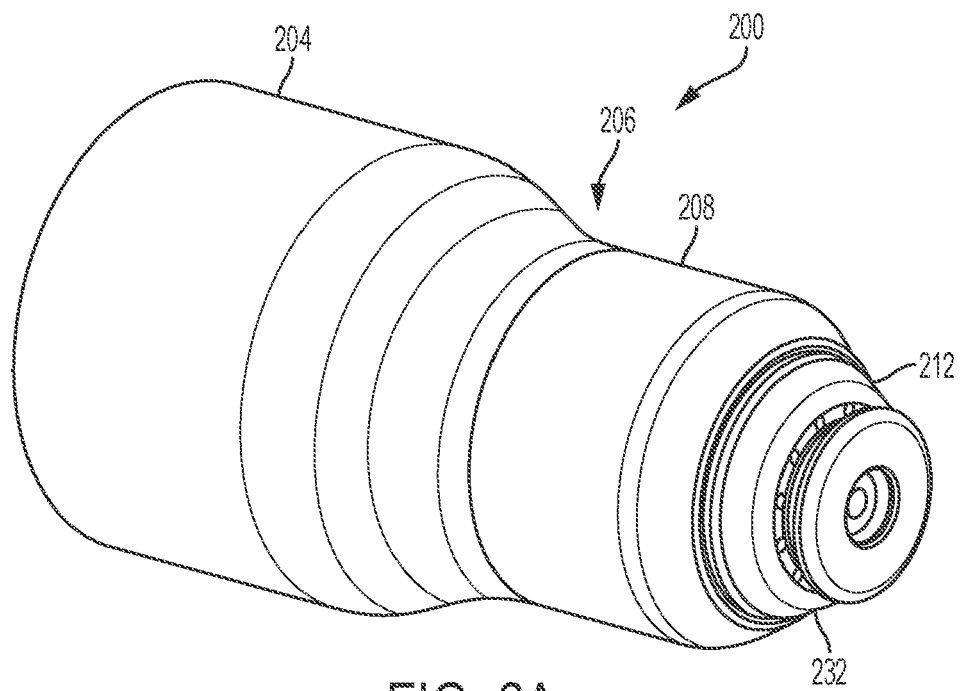


FIG. 2A

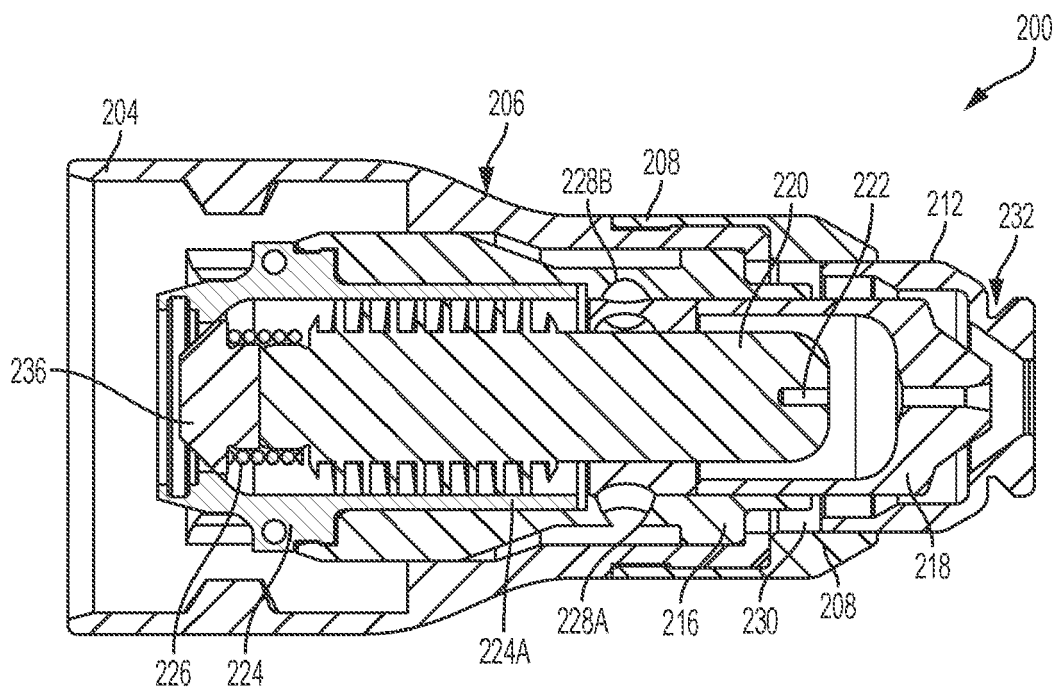


FIG. 2B

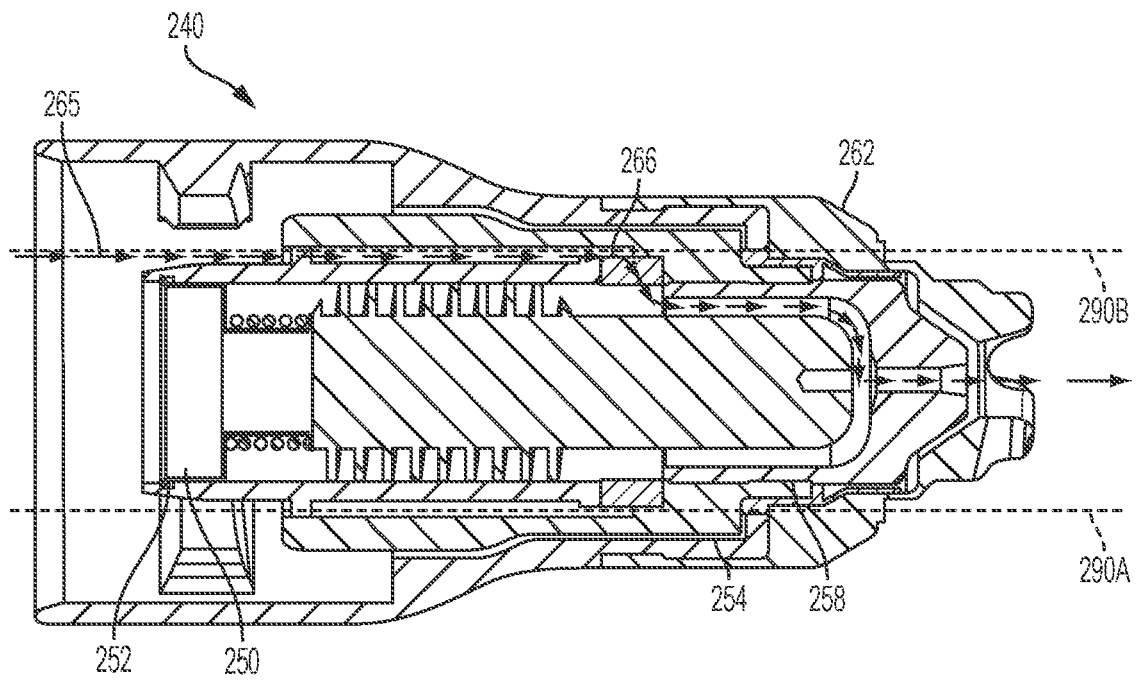


FIG. 2C

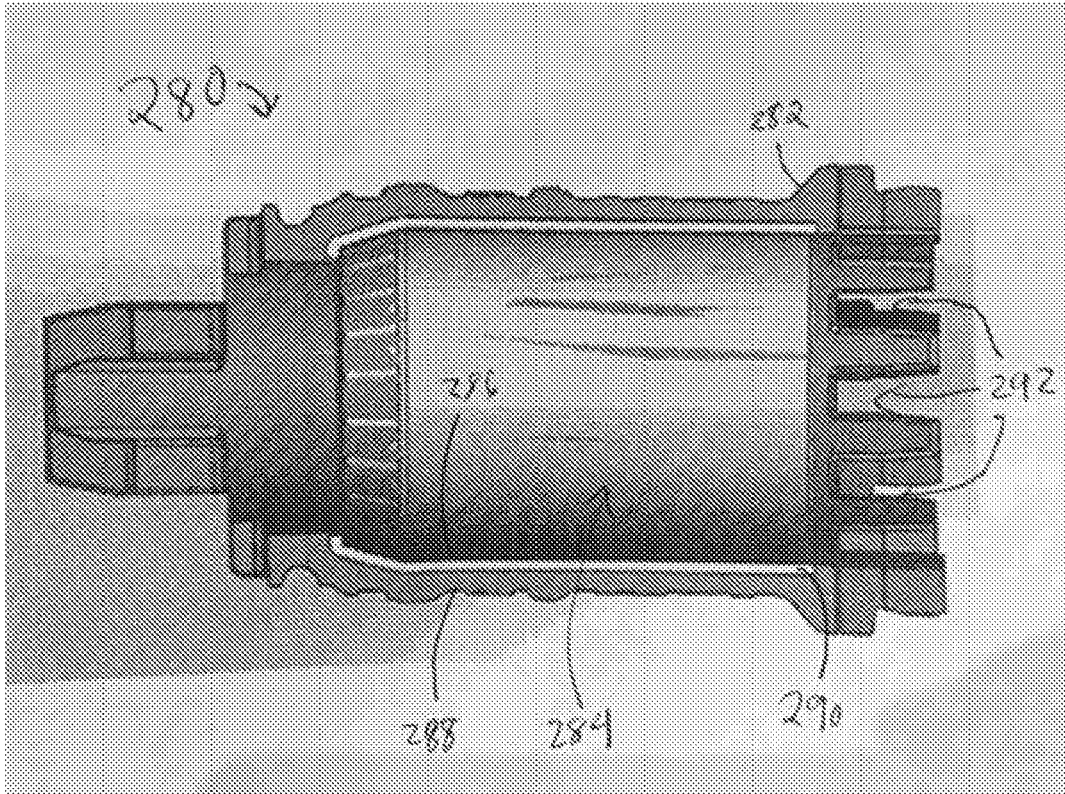


FIG. 2D

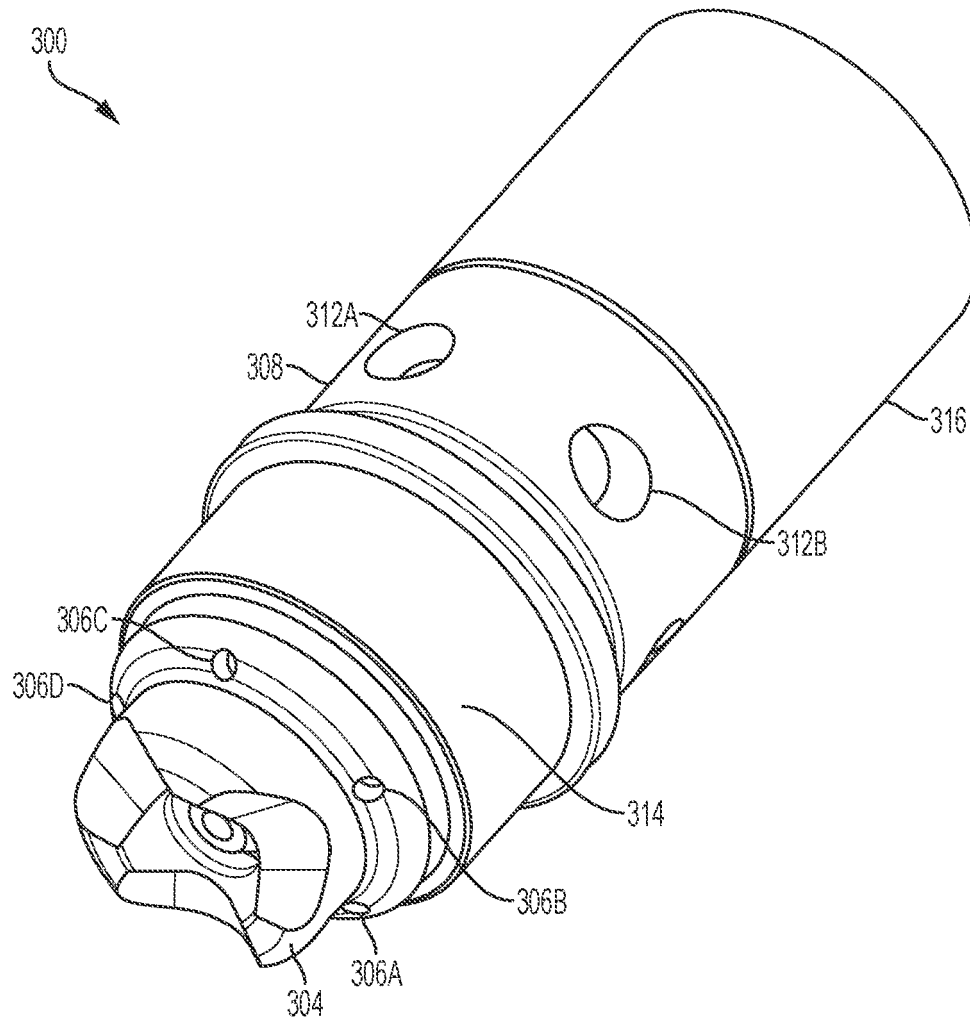


FIG. 3A

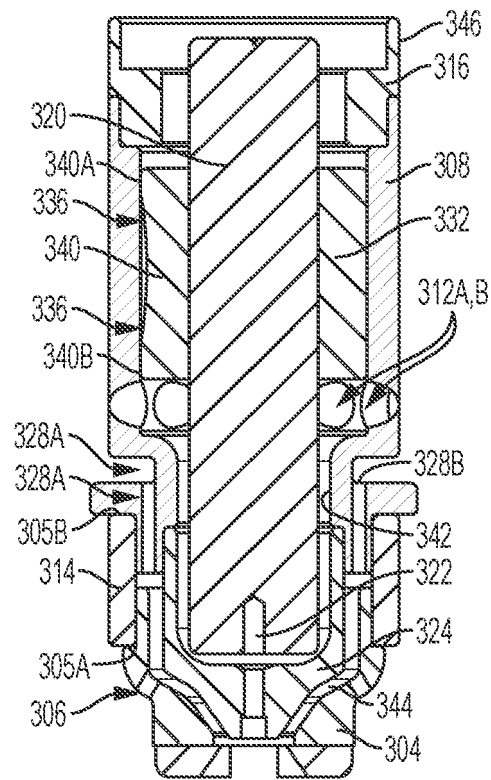


FIG. 3B

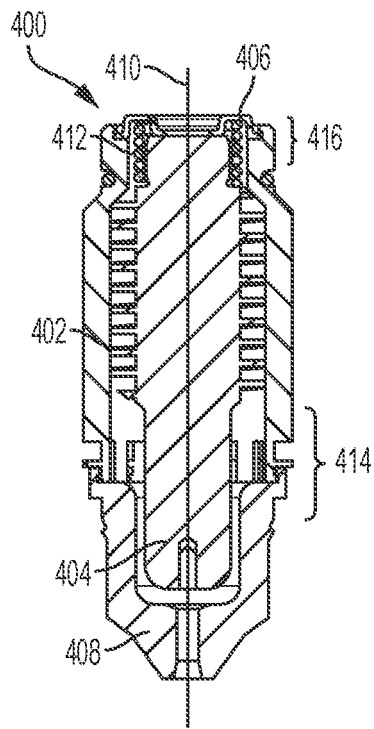


FIG. 4A

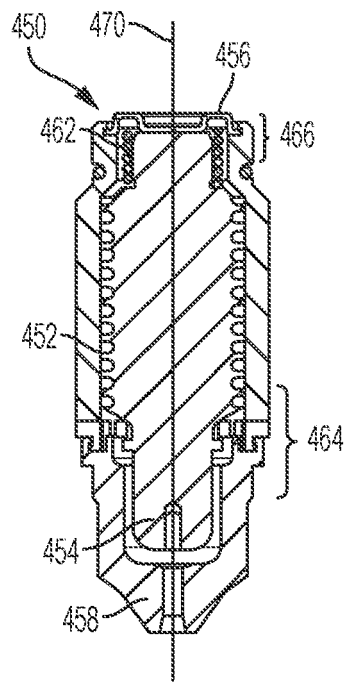


FIG. 4B

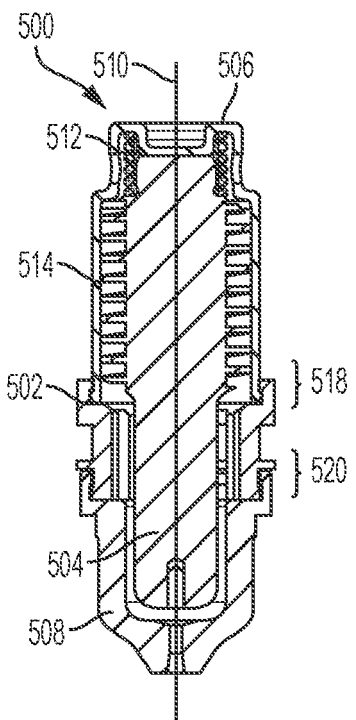


FIG. 5

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

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