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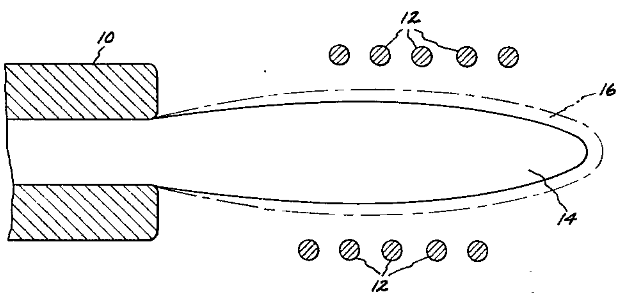
(54) **Method and apparatus for producing a plasma flow having a heated and broadened plasma jet.**

(57) A method for heating and broadening the plasma jet exhausting from a plasma gun includes directing the jet along the central axis of a downstream induction coil and passing a high frequency alternating current through the coil, so that the outer layers of the plasma jet are heated more than the center thereof, and the average temperature of the jet is increased. A preferred method for producing the plasma jet includes establishing a plasma discharge in a gas flowing along the central axis of a separate, upstream induction coil, by passing a high frequency alternating current through the coil, and directing the gas flow and at least a portion of the plasma discharge through a throated passage to form a plasma jet. In accordance with a preferred embodiment, an apparatus for carrying out the invention includes a housing having a flow channel with an inlet opening and an outlet opening, a throat region between the inlet and outlet openings, first and second induction coils disposed around the inlet and outlet ends, respectively, of the channel, means for introducing a high velocity flow of gas into the channel, and means for passing high frequency alternating currents through each of the induction coils.



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METHOD AND APPARATUS FOR PRODUCING A PLASMA FLOW HAVING A HEATED AND BROADENED PLASMA JET

Background of the Invention

This invention relates to a method and apparatus for producing a plasma flow having a heated and broadened plasma jet. More particularly, it relates to the use of an induction coil to heat the plasma jet exhausting from a plasma spray gun.

Plasma guns are frequently used to deposit a material, such as metal or ceramic, on an object to be coated or shaped, typically referred to as a target. In a typical plasma spray operation, the material to be deposited is formed into powder particles, and the particles are injected into the plasma. Ideally, hot streaming gases from the plasma heat the powder particles to their melting point and accelerate them in preparation for deposit on the target. If all of the injected particles are equally heated and accelerated, and if all of the particles stay in the plasma stream while being transported to the target, the deposited material is of high, uniform density and high strength. In practice, however, such is not the case. Typically, the deposits resulting from conventional plasma spray operations have higher density and strength in the area known as the "sweet spot", in the center of the deposit, than in the "fringe area" around the center of the deposit.

One of the causes of the degraded material properties in the "fringe area" is non-uniform heating and acceleration of the powder particles. In many conventional plasma guns, the temperature of the plasma decreases rapidly from the center of the plasma stream to its outer radius. Optimal heating and accleration of injected particles occurs within a relatively narrow radius from the center of the plasma stream. Furthermore, the overall temperature of the plasma stream decays rapidly as the plasma flows toward the target. The average temperature of a radial cross section of the plasma stream located near the target is significantly lower than the average temperature of a similar cross section located where the plasma stream exhausts from the plasma gun. Hence, the temperature of the plasma stream decays in both the axial and the radial directions. The result of this temperature decay is that particles being transported to the target in the outer layers of the plasma stream may not be heated enough to be molten when they are deposited on the target, or, even if molten when they exhaust from the plasma gun, may solidify before reaching the target. Consequently, a plasma stream is desired that provides a larger radius of optimal particle heating and that maintains injected particles in a molten state until they are deposited on the target.

Accordingly, it is an object of the present invention to provide a method for heating and broadening the plasma jet exhausting from a plasma spray gun.

It is a further object of the present invention to provide a method for using an induction coil in order to heat and broaden the plasma jet exhausting from a plasma spray gun.

It is another object of the present invention to provide a method for producing a plasma flow exhibiting an improved temperature distribution and a broadened plasma jet.

It is also an object of the present invention to provide an apparatus for heating and broadening the plasma jet exhausting from a plasma gun.

It is still another object of the present invention to provide a plasma flow nozzle having an induction coil to heat a gas stream flowing therethrough.

It is yet another object of the present invention to provide an apparatus for producing a plasma flow having a heated and broadened plasma jet.

Summary of the Invention

In accordance with one embodiment of the present invention, a method for heating and broadening the plasma jet exhausting from a plasma gun comprises directing the plasma jet along the central axis of an induction coil and passing a high frequency alternating current through the coil, so that the outer layers of the plasma jet are heated more than the center of the jet, and so that the average temperature of the jet is increased. A preferred method for producing a plasma flow having a hotter and broader jet than is conventionally provided comprises: establishing a plasma discharge in a gas flowing along the central axis of a first, upstream induction coil, by passing a high frequency alternating current through the coil; producing a plasma jet by directing the gas, and at least a portion of the plasma discharge, through a throated passage; and heating the plasma jet emitted from the throated passage, by the method described above, using a second, downstream induction coil.

In accordance with another embodiment of the present invention, an apparatus for carrying out the present invention comprises a plasma gun having an inlet and an outlet, in which a plasma discharge may be established so that a plasma jet exhausts through the plasma gun outlet. A heater housing having a flow channel defined therein is connected in flow communciation with the outlet of the plasma gun so that the plasma jet is directed through the flow channel. The apparatus also includes a heater induction coil disposed around the outside of the flow channel and means for passing a high frequency alternating current through the coil in order to heat the plasma jet. In a preferred embodiment, the plasma gun used in the above apparatus includes a housing having a flow channel with an inlet opening and an outlet opening, a throat region between the inlet and outlet ends of the channel, and another induction coil disposed around the inlet end of the flow channel. An apparatus for producing a plasma flow having a heated and broadened plasma jet includes the apparatus described above and further comprises means for introducing a high velocity flow of gas into the plasma gun and means for passing high frequency alternating currents through each of the induction coils.

Brief Description of the Drawings

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention itself, however, both as to its organization and its method of practice, together with further objects and advantages thereof, may best be understood by reference to the following description taken in conjunction with the accompanying drawings, in which:

Figure 1 is a side elevation, cross-sectional view schematically illustrating one embodiment of the present invention;

Figure 2 is a view similar to Figure 1 schematically illustrating another embodiment of the present invention; and

Figure 3 is a view similar to Figure 2 schematically illustrating still another embodiment of the present invention.

Detailed Description of the Invention

The instant applicants have found that, to produce a plasma spray deposit with a larger "sweet spot" and reduced "fringe area," the plasma jet exhausting from the plasma spray gun used to make the deposit should be further heated and broadened. In accordance with the present invention, a method for doing so comprises directing the plasma jet along the central axis of a downstream induction coil and passing a high frequency alternating current through the downstream induction coil, so as to both heat the outer layers of the plasma jet and increase the average temperature of the jet. Preferably, the magnitude and frequency of the high frequency alternating current flowing through the induction coil are chosen such that the current flow produces a power output of between about 20 kilowatts and 100 kilowatts. The frequency of the current oscillation is preferably between about 500 kHz and 10 MHz. As schematically illustrated by the side elevation, cross-sectional view of Figure 1, plasma jet 14 exhausts from plasma spray gun 10 and flows along the central axis of a downstream induction coil 12 comprised of several induction coil winding turns. When a high frequency alternating current is passed through induction coil 12, a high frequency magnetic field is produced, through which energy is coupled into plasma jet 14. This energy transfer heats the outer layers of plasma jet 14 more than it heats the center thereof, thereby reducing the temperature decay of plasma jet 14 in the radial direction. Thus, plasma jet 14 can be made to have a substantially flat radial temperature distribution. Heating of plasma jet 14 in this manner results in a broader, larger diameter plasma jet stream, as illustrated in Figure 1 by plasma jet layer 16. With a larger diameter plasma jet stream, particles injected into the stream can more easily be kept within the confines of the plasma stream. Furthermore, with a larger diameter stream, the area within the stream where the plasma temperature is optimal has a larger radius. Heating of plasma jet 14 by energy transfer from induction coil 12 also increases the average temperature of plasma jet 14, thereby reducing the effects on particle melting of temperature decay in the axial direction. As a result of these three effects, that is, reducing radial temperature decay, broadening the plasma jet, and increasing the average jet temperature, particles injected into the plasma stream are more uniformly heated and more completely melted before being deposited on a target. This result is especially significant for particles in the area of the boundary layer. Particles which, without heating and broadening of the plasma jet by the method of the present invention, may not be heated to the molten state or which may resolidify before reaching the target, will, when the instant invention is utilized, be better heated and more completely melted. Another advantage provided by the present invention is that heating of the gas around the outside of the plasma jet, produced by high frequency alternating current passing through the downstream induction coil, increases the friction between the plasma jet and the gas surrounding it, thereby decreasing the velocity of the jet. This decreased jet velocity results in a longer residence time of injected particles within the hot streaming gases of the plasma jet and, therefore, improved heating of the particles. It can thus be seen that the method of the present invention results in a larger number of properly heated particles hitting the target.

One embodiment of an apparatus suitable for practicing the method described above for heating and broadening the plasma jet from a plasma gun is schematically illustrated by the side elevation, cross-sectional view of Figure 2. Plasma gun 18 includes inlet 22 for receiving a high velocity flow of gas (not illustrated in Figure 2). Plasma gun 18 also includes cathode 26 and anode 20 for producing an electrical arc and thereby initiating a plasma discharge in the gas, as shown in Figure 2 by arc discharge 28. Plasma gun 18 also includes outlet 24 for exhausting at least a portion of the plasma discharge from plasma gun 18, as plasma jet 32. Heater housing 34 having flow channel 30 defined therethrough is connected to plasma gun 18 so that flow channel 30 is in flow communication with outlet 24 of plasma gun 18, and so that plasma jet 32 is directed through flow channel 30. Heater induction coil 36 is disposed around the outside of flow channel 30. In the embodiment shown in Figure 2, induction coil 36 is further disposed so that the longitudinal axis of the coil is located coaxially with the longitudinal axis of flow channel 30. Also, in the embodiment shown, flow channel 30 is cylindrically shaped, and induction coil 36 is helically wound around the outside of flow channel 30. The apparatus further includes conventional means (not illustrated in Figure 2) electrically connected to induction coil 36 for passing a high frequency alternating current therethrough, in order to heat the outer layers of plasma jet 32 more than the center thereof, and to increase the average temperature of plasma jet 32.

Although plasma gun 18 is shown in Figure 2 as comprising a direct current arc-jet plasma gun, it may also comprise an electrodeless, radio frequency plasma gun, as shown in Figure 3. Figure 3 is a side elevation, cross-sectional view schematically illustrating a plasma flow nozzle in accordance with another embodiment of the present invention. The nozzle comprises housing 40 having main flow channel 42 defined therein, with inlet opening 44 located at one end of flow channel 42 and disposed in flow communication therewith, and outlet opening 48 located at the opposite end of flow channel 42 and also disposed in flow communication therewith. In the embodiment shown, throat region 46, having reduced cross-sectional flow area, is disposed in flow channel 42 and located between inlet opening 44 and outlet opening 48, for accelerating gas passing through throat region 46 and forming a jet stream downstream thereof. However, it should be understood that the jet stream may also be formed by other conventional means. First or upstream induction coil 50 is located at the inlet end of flow channel 42, and second or downstream induction coil 52 is located at the outlet end of flow channel 42. First induction coil 50 and second induction coil 52 are each disposed around the outside of flow channel 42. In the embodiment shown in Figure 3, first and second induction coils 50 and 52 are further disposed so that their longitudinal axes are each located coaxially with respect to the longitudinal axis of flow channel 42. Also, in the embodiment shown, flow channel 42 is cylindrically shaped, and first and second induction coils 50 and 52 are each helically wound around the outside of flow channel 42. For applications where it is desirable, first and second induction coils 50 and 52 may be electrically connected, so that they form a single electrical circuit.

In accordance with another embodiment of the present invention, a method for producing a plasma flow having a heated and broadened plasma jet comprises directing a gas flow, in which a plasma is to be established, at a high velocity along the central axis of a first, upstream induction coil, and passing a high frequency alternating current through the first induction coil so as to heat the gas and initiate a plasma discharge therein. The method includes forming a plasma jet from the gas flow and at least a portion of the plasma discharge. One method for forming the plasma jet is to direct the gas flow and a portion of the plasma discharge through a throated passage having reduced cross-sectional flow area, in order to accelerate the gas flow through the throated passage and to produce a plasma jet. The method further includes directing the resulting plasma jet along the central axis of a second, downstream induction coil. A high frequency alternating current is passed through the second induction coil, so as to heat the outer layers of the plasma jet more than the center thereof, and to increase the average temperature of the plasma jet. In a preferred embodiment, the high frequency alternating current flowing through the first induction coil produces a power output of between about 20 kilowatts and 100 kilowatts, and the high frequency current flowing through the second induction coil similarly produces a power output of between about 20 kilowatts and 100 kilowatts. For each of the coils, the current flowing through the coil preferably comprises current oscillating at a frequency of between about 500 kHz and 10 MHz. Also preferably, the velocity of the gas flow along the central axis of the first induction coil is between about 5 meters per second and 50 meters per second. The plasma flow nozzle of Figure 3 is especially suitable for carrying out this embodiment of the invention. An apparatus for producing a plasma flow having a heated and broadened plasma jet includes the plasma flow nozzle shown therein, and further comprises conventional means (not illustrated in Figure 3) for introducing a high velocity flow of gas into flow channel 42, connected in flow communication with inlet opening 44. The apparatus also comprises conventional means (also not illustrated in Figure 3) electrically connected to first induction coil 50, for passing a high frequency alternating current therethrough, in order to heat gas flowing along the central axis of coil 50, and to initiate plasma discharge 56 in the gas flowing through flow channel 42. The apparatus further includes conventional means (similarly not illustrated in Figure

3) electrically connected to second induction coil 52, for passing a high frequency alternating current therethrough, in order to heat the outer layers of jet stream 58, formed from gas passing through throat region 56, more than the center of jet stream 58 is heated, and to increase the average temperature of jet stream 58. A plasma flow produced in accordance with this embodiment of the invention has, in addition to the desirable features described above, the advantage of being characterized by a broad and long plasma discharge, with a nearly flat radial temperature distribution. Furthermore, the flow velocity of the gas in which the plasma is established may be quite low, so that the residence time of particles injected into the plasma may be quite long. Also, the plasma density can be made quite high, thereby facilitating heat transfer from the plasma to the injected particles, and further improving particle melting and acceleration and finished characteristics of the target.

The foregoing describes a method for heating and broadening the plasma jet exhausting from a plasma spray gun, by using a downstream induction coil to heat and broaden the plasma jet. The present invention also provides a method for producing a plasma flow with less temperature decay in both the radial and the axial directions. The present invention further provides a plasma flow nozzle having an induction coil to heat a gas stream flowing therethrough, and an apparatus for producing a plasma flow having a heated and broadened plasma jet.

While the invention has been described in detail herein in accord with certain preferred embodiments thereof, many modifications and changes therein may be effected by those skilled in the art. For example, while the apparatus has been described and shown in the Figures as having a generally circular cross section, it should be appreciated that other cross-sectional shapes may be employed, such as rectangular or elliptical cross sections. Furthermore, although the induction coil windings are shown in Figures 2 and 3 as being embedded in a housing, the windings may also be mounted on either the inner surface or the outer surface of the housing. Additionally, while housing 34 of Figure 2 and housing 40 of Figure 3 have both been indicated as comprising quartz, other temperature resistant electrically insulating materials may also be used. Housings 34 and 40 may even comprise metal, if provisions are made so that absorption of radio frequency energy, produced by the induction coils, in each of housings 34 and 40 is minimized. Also, while cathode 26 and anode 20 of Figure 2 have been shown as comprising metal, other electrically conductive materials may be used. Accordingly, it is intended by the appended claims to cover all such modifications and changes as fall within the true spirit and scope of the invention.

The invention claimed is:

1. A method for heating and broadening the plasma jet exhausting from a plasma spray gun, comprising:

directing said plasma jet along the central axis of an induction coil; and

passing a high frequency alternating current through said induction coil, so as to both heat the outer layers of said plasma jet more than the center thereof, and to increase the average temperature of said plasma jet.

2. The method of claim 1 wherein said high frequency alternating current flowing through said induction coil produces a power output of between about 20 kilowatts and 100 kilowatts.

3. The method of claim 1 wherein said high frequency alternating current comprises current oscillating at a frequency of between about 500 kHz and 10 MHz.

4. A method for producing a plasma flow having a heated and broadened plasma jet, comprising:

directing a gas flow, in which gas flow a plasma is to be established, at a high velocity along the central axis of a first induction coil;

passing a high frequency alternating current through said first induction coil, so as to heat said gas and initiate a plasma discharge therein;

forming a plasma jet from said gas flow and at least a portion of said plasma discharge;

directing said plasma jet along the central axis of a second induction coil; and

passing a high frequency alternating current through said second induction coil, so as to both heat the outer layers of said plasma jet more than the center thereof, and to increase the average temperature of said plasma jet.

5. The method of claim 4 wherein the velocity of said gas flow along the central axis of said first induction coil is between about 5 meters per second and 50 meters per second.

6. The method of claim 4 wherein said high frequency alternating current flowing through said first induction coil produces a power output of between about 20 kilowatts and 100 kilowatts, and said high frequency alternating current flowing through said second induction coil also produces a power output of between about 20 kilowatts and 100 kilowatts.

7. The method of claim 4 wherein said high frequency alternating current flowing through said first induction coil comprises current oscillating at a frequency of between about 500 kHz and 10 MHz, and said high frequency alternating current flowing through said second induction coil also comprises current oscillating at a frequency of between about 500 kHz and 10MHz.

8. The method of claim 4 wherein said step of forming a plasma jet comprises directing said gas flow and at least a portion of said plasma discharge through a throated passage having reduced cross-sectional flow area, in order to accelerate said gas flow through said throated passage and to produce a plasma jet.

9. Apparatus for producing a plasma jet, comprising:

a plasma gun, having an inlet and an outlet, for receiving a high velocity flow of gas, initiating a plasma discharge in said gas, and exhausting at least a portion of said plasma discharge through said plasma gun outlet in the form of a plasma jet;

a heater housing having a flow channel defined therethrough, with said flow channel being in flow communication with said outlet of said plasma gun so that said plasma jet is directed through said flow channel;

a heater induction coil disposed around the outside of said flow channel;

means for passing a high frequency alternating current through said heater induction coil, said means being electrically connected to said coil, so as to both heat the outer layers of said plasma jet more than the center thereof, and to increase the average temperature of said plasma jet.

10. The apparatus of claim 9 wherein said heater induction coil is further disposed so that the longitudinal axis of said coil is located coaxially with the longitudinal axis of said flow channel.

11. The apparatus of claim 10 wherein said flow channel is cylindrically shaped and said heater induction coil is helically wound around the outside of said flow channel.

12. The apparatus of claim 9 wherein said plasma gun comprises a direct current arc-jet plasma gun.

13. The apparatus of claim 9 wherein said plasma gun comprises an electrodeless, radio frequency plasma gun.

14. A plasma flow nozzle, comprising:

a housing having a main flow channel defined therein;

an inlet opening located at one end of said flow channel and disposed in flow communication therewith;

an outlet opening located at the opposite end of said flow channel and disposed in flow communication therewith;

a first induction coil located at the inlet end of said flow channel, said first induction coil being disposed around the outside of said flow channel; and

a second induction coil located at the outlet end of said flow channel, said second induction coil being disposed around the outside of said flow channel.

15. The plasma nozzle of claim 14 wherein said first and second induction coils are further disposed so that the longitudinal axis of each said induction coil is located coaxially with the longitudinal axis of said flow channel.

16. The plasma nozzle of claim 15 wherein said flow channel is cylindrically shaped and said first and second induction coils are each helically wound around the outside of said flow channel.

17. The plasma nozzle of claim 14 wherein said first and second induction coils are electrically connected, so that they form a single electrical circuit.

18. The plasma nozzle of claim 14 further comprising a throat region, having reduced cross-sectional flow area, disposed in said main flow

channel and located between the inlet end and the outlet end thereof, for accelerating gas passing through said throat region and forming a plasma stream downstream of said throat region.

19. Apparatus for producing a plasma flow having a heated and broadened plasma jet, including the plasma flow nozzle of claim 14 and further comprising:

means for introducing a high velocity flow of gas into said flow channel, connected in flow communication with said inlet opening;

means for passing a high frequency alternating current through said first induction coil, said means being electrically connected to said first induction coil, for heating gas flowing through said flow channel along the central axis of said first induction coil, and for initiating a plasma discharge therein; and

means for passing a high frequency alternating current through said second induction coil, said means being electrically connected to said second induction coil, for heating the outer layers of a plasma stream formed from said gas, having said plasma discharge initiated therein, flowing through said flow channel, and for increasing the average temperature of said plasma stream.

20. Apparatus for producing a plasma flow having a heated and broadened plasma jet, including the plasma flow nozzle of claim 16 and further comprising:

means for introducing a high velocity flow of gas into said flow channel, connected in flow communication with said inlet opening;

means for passing a high frequency alternating current through said first induction coil, said means being electrically connected to said first induction coil, for heating gas flowing through said flow channel along the central axis of said first induction coil, and for initiating a plasma discharge therein; and

means for passing a high frequency alternating current through said second induction coil, said means being electrically connected to said second induction coil, for heating the outer layers of a plasma stream formed from said gas, having said plasma discharge initiated therein, flowing through said flow channel, and for increasing the average temperature of said plasma stream.

21. Apparatus for producing a plasma flow having a heated and broadened plasma jet, including the plasma flow nozzle of claim 17 and further comprising:

means for introducing a high velocity flow of gas into said flow channel, connected in flow communication with said inlet opening;

means for passing a high frequency alternating current through said electrically connected first and second induction coils, said means being electrically connected to said single electrical circuit, for heating gas flowing through said flow channel and initiating a plasma discharge therein, and for heating a plasma stream formed from said gas, having said plasma discharge initiated therein, flowing through said flow channel, in order to heat the outer layers of said plasma stream more than the center thereof, and to increase the average temperature of said plasma stream.

22. Apparatus for producing a plasma flow having a heated and broadened plasma jet, including the plasma flow nozzle of claim 18 and further comprising:

means for introducing a high velocity flow of gas into said flow channel, connected in flow communication with said inlet opening;

means for passing a high frequency alternating current through said first induction coil, said means being electrically connected to said first induction coil, for heating gas flowing through said flow channel along the central axis of said first induction coil, and for initiating a plasma discharge therein; and

means for passing a high frequency alternating current through said second induction coil, said means being electrically connected to said second induction coil, for heating the outer layers of said plasma jet stream formed from gas passing through said throat region, and for increasing the average temperature of said jet stream.

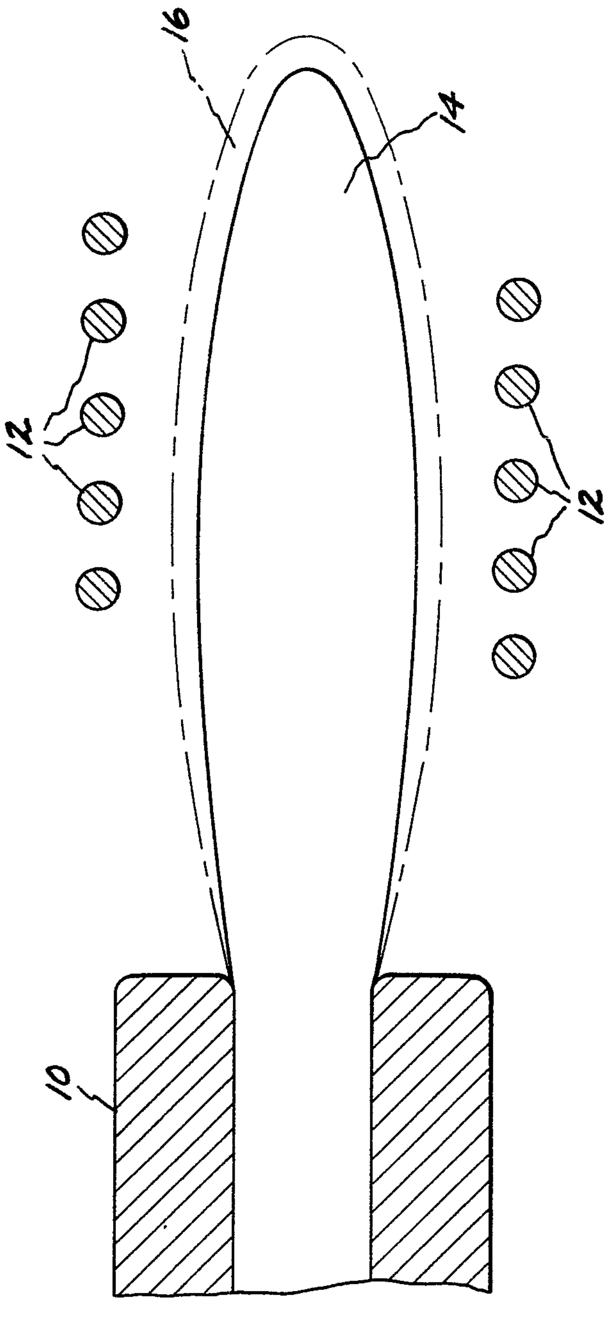

FIG. 1

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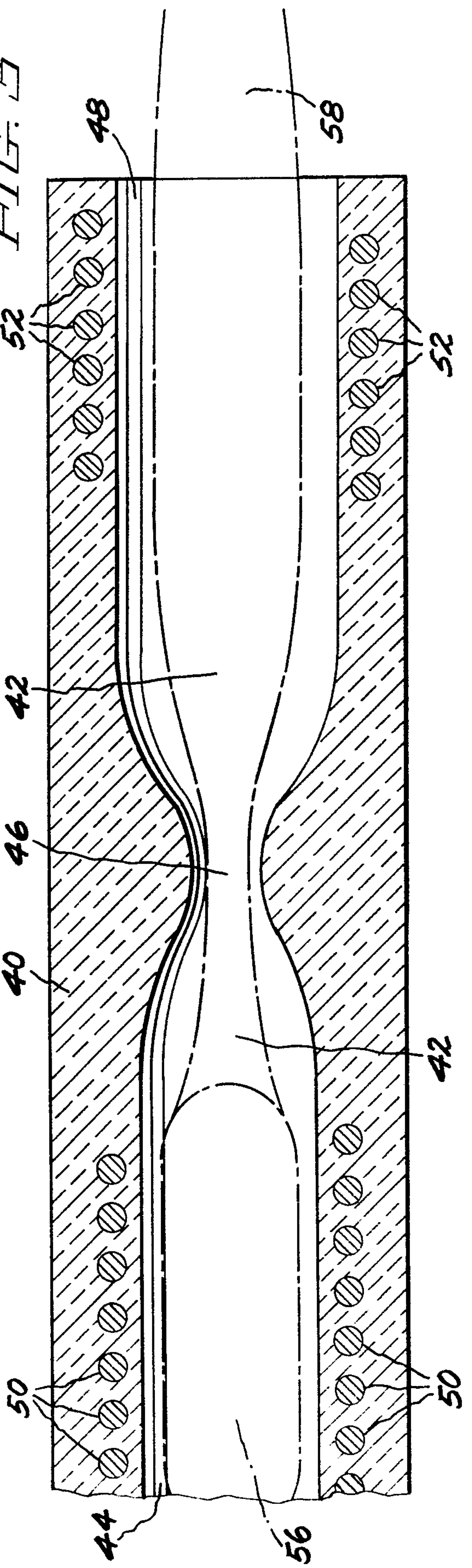
FIG. 3



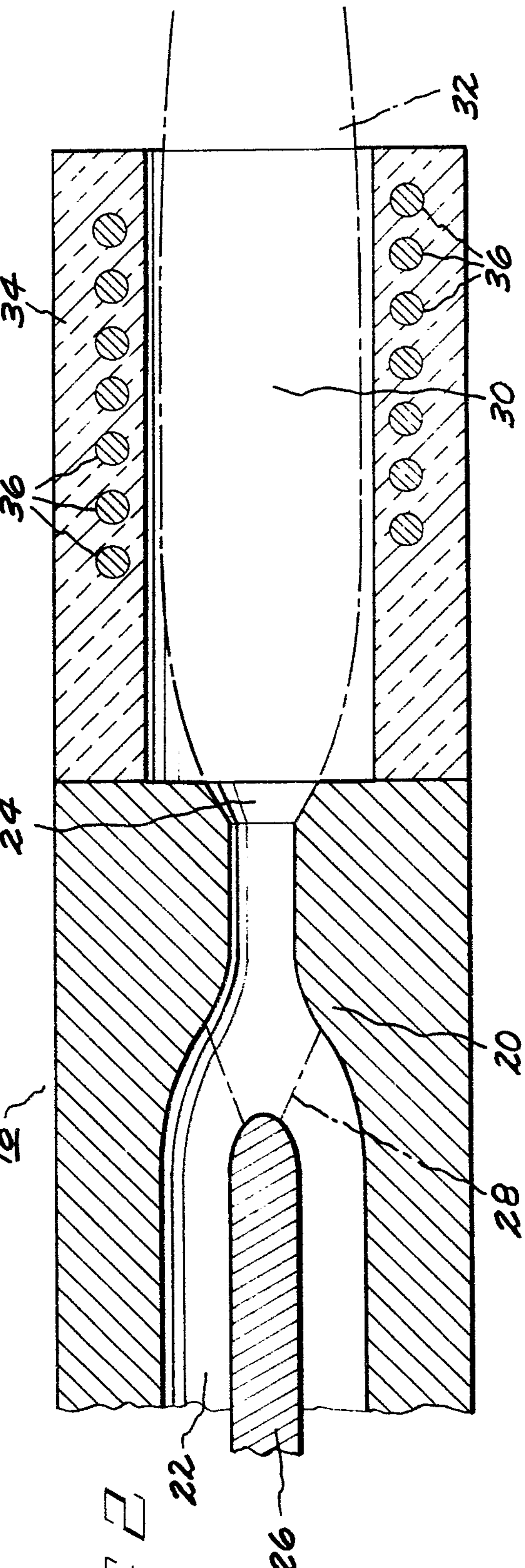


FIG. 2