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Sheer et al.

[54] **METHOD AND APPARATUS FOR PROJECTING MATERIALS INTO AN ARC DISCHARGE**

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[63] Continuation-in-part of Ser. No. 159,616, July 6, 1971, abandoned.

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[58] **Field of Search .... 315/111;** 313/231, 231.4; 219/75, 121 P

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[57]   **ABSTRACT**

An improved method for energizing reactive materials by means of an arc discharge is provided by interposing a stream of shielding gas between the cathode producing the arc and the reactive material. An apparatus for so interposing a shielding gas includes a conical shroud around the cathode defining therebetween an annular passage for admitting a shielding gas stream.

13 Claims, 3 Drawing Figures

Fig. 1.

Fig. 2.

Fig. 3.
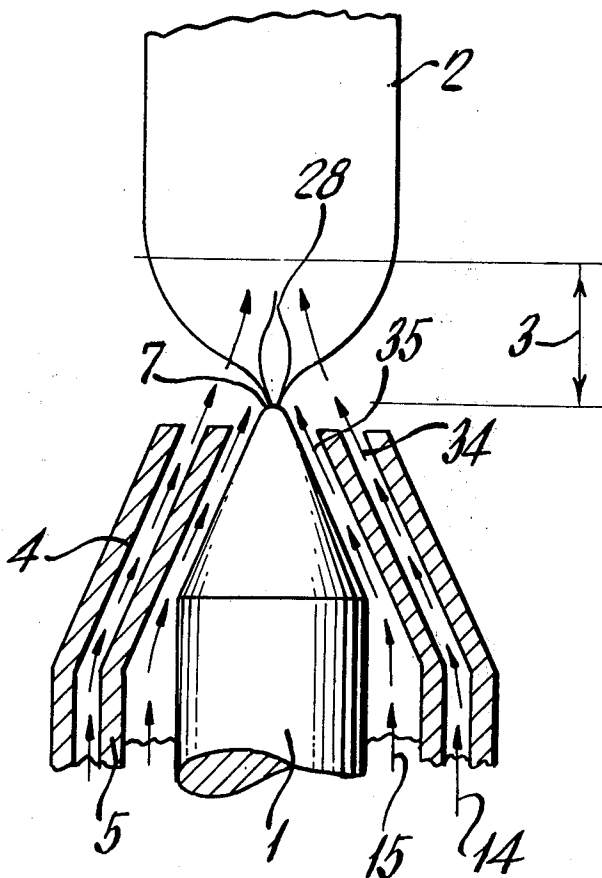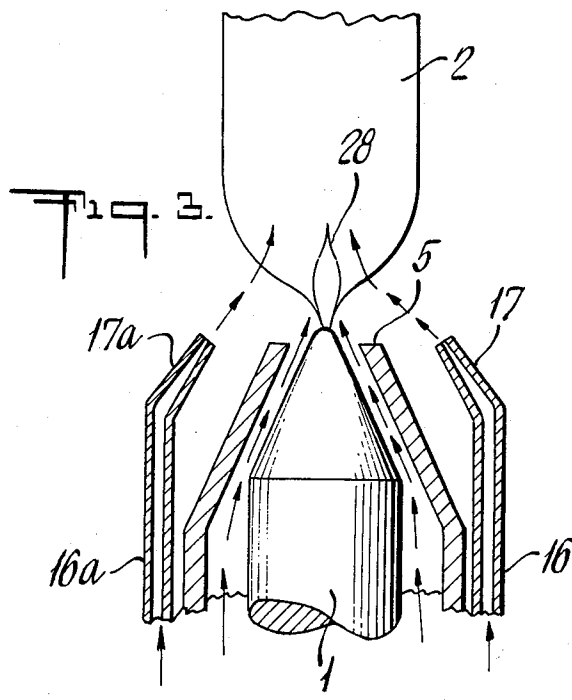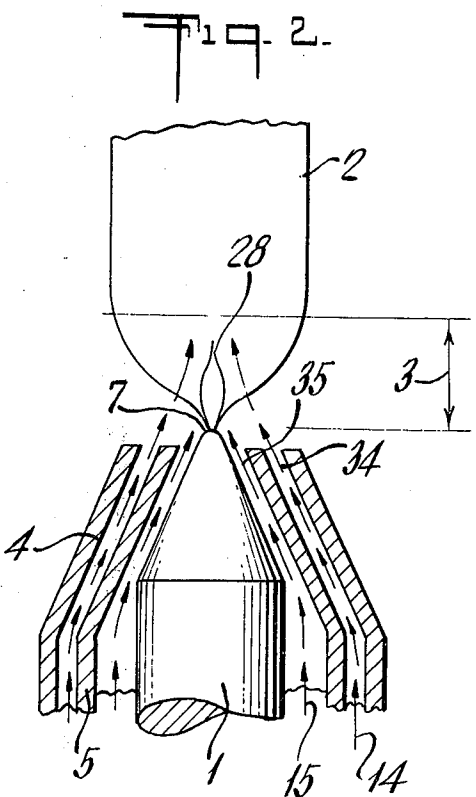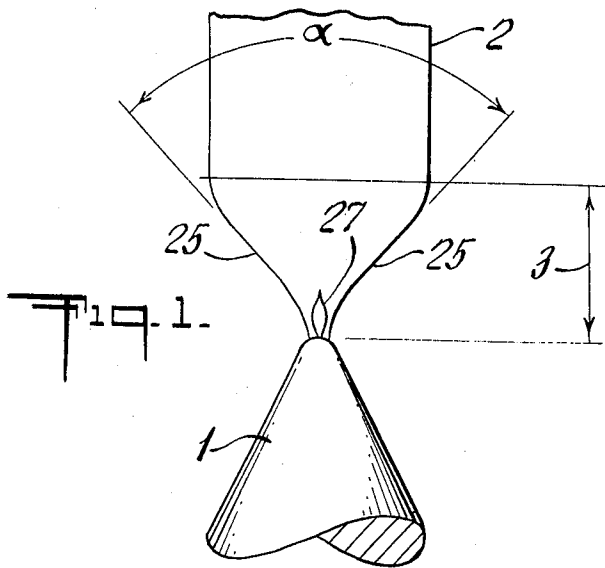
METHOD AND APPARATUS FOR PROJECTING MATERIALS INTO AN ARC DISCHARGE

CROSS REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of application Ser. No. 159,616, filed July 6, 1971, now abandoned.

BACKGROUND OF THE INVENTION

This invention relates to improved apparatus and method for producing chemical and physical changes in substances by exposure of reactive materials to direct current electric arcs. More particularly, the present invention relates to a method and apparatus for exposing materials to the high energy region of a conduction column of a free-burning electric arc.

Various techniques are known for generating a continuous stream of plasma by means of an electric arc. As would be expected, there are practical problems associated with each technique for generating the plasma. Moreover, each method of generation affects the character of the plasma produced. Utilization of the plasma to bring about chemical and physical changes in various substances is even more complex.

A novel and very effective technique for efficiently energizing reactive materials in the conduction column of free-burning electric arc involves forcefully injecting the substance along a cathode having a conical tip into the contraction zone of the column. This technique takes advantage of the so-called cathode jet effect due to the contraction of the arc column near the cathode. In effect, under the right conditions the plasma moves away from the cathode with a concomitant decrease in the pressure at the base of the contraction zone so that the arc in this region aspirates gas from the surrounding atmosphere to form a continuous cathode plasma jet. The contraction zone, by virtue of this aspiration, serves as an "injection window" through which reactive materials may be injected directly into the arc column at flow rates greater than the natural aspiration rate without disturbing the stability of the arc. The reactive materials may be gases or gases containing an entrained condensed phase.

One of the difficulties associated with the aforementioned technique is preventing cathode erosion detrimental to the continuous performance of the arc.

In some instances cathode erosion appears to be a result of direct impingement of reactive material upon the cathode tip. Typically, the cathode surface at the cathode spot, i.e., the area where electrons are emitted from the cathode into the arc discharge, and a portion of the surface behind the cathode spot operates at a very high temperature, for example, at a temperature greater than 2000°C. At such high temperature numerous chemical reactions can take place. Also, when a solid material is entrained in a fluid medium and forcefully projected along the tip of the cathode into and through the arc discharge, invariably some of the solid material may come into contact with the surface of the cathode tip. Upon contact with this surface many of these powders will fuse thereby covering the surface of the cathode with a molten film of the powder material. Additionally, of course, the solids may also chemically react with the cathode material with the concomitant result that the cathode tip tends to chemically ablate faster than is desirable. There is even a considerable amount of evidence to indicate that direct impinge-

ment of the cathode with reactive material is not the root cause of cathode erosion but rather that highly reactive species are generated in the column which back diffuse and attack the cathode. In any event these processes are detrimental to the stability of the arc and indeed affect the commercial utility of plasma jet systems. Consequently, there is a need for improved methods and apparatus for energizing fluid materials in the plasma jet that efficiently utilize the energy of the arc while minimizing damage to cathode surfaces and maximizing arc stability.

SUMMARY OF THE INVENTION

In one aspect, the present invention provides an improved means for energizing a reactive material in the conduction column of an arc discharge between an anode and a cathode having a conical tip. The reactive material is forcefully projected along the conical tip of the cathode into the arc column via the contraction zone boundary and through the arc discharge. Interposed between the reactive material and the conical tip of the cathode in a direction parallel to the reactive material is a stream of gas which is not active at the temperature of the arc. This gas substantially protects the cathode from coming in contact with the fluid medium and is referred to herein as the shielding gas. Additionally the shielding gas and reactive material effectively widens the conduction column in the region in the vicinity of the cathode thereby facilitating further injection of material into the arc column.

In another aspect of the present invention, an improved means for energizing powders in the conduction column of a free-burning electric arc is provided by forcefully projecting a solid entrained fluid medium along the conical tip of the cathode into and through the arc discharge, while simultaneously interposing between the entrained solid and the cathode a stream of shielding gas.

In yet another aspect of the present invention, an apparatus is provided for projecting reactive materials into the contraction zone at the cathode of an arc discharge between an anode and a cathode having a conical tip. The apparatus comprises a conical shroud forming an annular passage around the conical tip of the cathode. The annular passage serves as a conduit for admitting a stream of shielding gas along the conical tip between the tip and reactive materials admitted by means of an annular passage defined by a second conical shroud surrounding the first conical shroud.

Alternatively, a plurality of nozzles are spaced around the periphery of the cathode tip to deliver reactive material substantially parallel with the surface of the tip, and preferably normal to the contraction zone or "injection window" of the arc column, while a protective stream of shielding gas is admitted between the reactive material and the cathode tip.

These and other features of the invention will be more fully understood from the description which follows.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram showing the plasma bubble and illustrating the arc column contraction, the degree of contraction being determined by the angle α in the vicinity of a cathode having a conical tip.

FIG. 2 is an enlarged cross-section of the embodiment of the present invention showing the enlargement

of the plasma bubble and the method of operation of the invention with a cathode provided with a second concentric conical shroud.

FIG. 3 illustrates an alternative method of practicing the present invention by providing nozzles for directing a stream of shielding gas along the conical tip of the cathode.

DETAILED DESCRIPTION

Referring to FIG. 1, when an arc is struck between an anode (not shown) and a cathode having a conical tip there occurs a contraction of the current carrying area in the transition region between the cathode 1 and the conduction column proper 2. This contraction is indicated as contraction zone 3. This contraction of the current carrying area in the transition region between the cathode 1 and the column proper 2 may also be defined by the angle α which is determined by extending lines tangent to the column boundary at the points of inflection 25 of the contraction. This contraction causes the natural cathode jet effect as will be explained subsequently.

The current density, and therefore the self-magnetic field due to the arc current, increases toward the cathode as a result of the contraction of the current carrying area. This non-uniform magentic field exerts a body force on the electrically conducting plasma propelling it in the direction of maximum decrease in magnetic field, i.e., along the arc axis away from the cathode tip. The streaming of plasma away from the cathode tip decreases the local pressure in the immediate vicinity of the cathode tip. The pressure decrease causes the arc to aspirate gas from the surrounding atmosphere. This mechanism establishes the well known natural cathode jet which has been observed to flow along the axis of the column away from the cathode tip in all arcs characterized by a contraction zone adjacent to the cathode.

In view of the fact that there exists an inwardly directed pressure gradient in the vicinity of the cathode tip, contraction zone 3 can serve as an "injection window" through which materials may be injected directly into arc column 2. Indeed, it has been found that feed flow rates of a magnitude much greater than that aspirated naturally can be injected into the column through the injection window without disturbing the stability of the arc. The effect of the forced convection is to increase both the current density and the voltage gradient in and near the contraction zone, thereby increasing the volume rate of energy dissipation within this portion of the column, making available the additional energy needed to heat the increased quantity of material which penetrates into the column. In short, the injection of a copious stream of gas into the column through the injection window is not only possible, but actually increases the heat transfer effectiveness of this part of the arc. However, the increase in gas convection rate does affect the angle α and if the angle α is reduced below about 40°, the amount of material that can be injected into the arc column 2 through the window is limited substantially.

Increased gas convection rates reduce the size of the "window" so to speak, thereby placing practical limits on efficient use of the arc. To achieve the effect described, the gas or reactive materials injected into the arc must be projected at a high velocity at least parallel

to the conical cathode surface and preferably normal to the contraction zone boundary.

By proper adjustment of the gas velocity at one angle of the cathode, the gas can be made to cross the column boundary in essentially the same and general direction as would be aspirated from the surrounding atmosphere in the absence of forced convection. The optimum cone angle for this purpose appears to be between 45° and 60°. The term "cone angle" refers to the vortex angle of the converging segment of the cathode cone. However, cone angles from 20° to 135° may be employed in the instant invention, depending partly on the material of the cathode and the type of fluid material injected into the arc.

In order to maintain the integrity of the conical tip, in accordance with the present invention the cone is protected or shielded against physical abrasion and chemical attack by reactive materials which are projected along the conical tip of the surface or which back diffuse from the column. This protection is afforded by interposing between the reactive material and the conical tip of the cathode a stream of shielding gas.

By shielding gas is meant any gas which is not active, i.e., chemically reactive toward the cathode material, at prevailing cathode temperatures during arc operation.

Typical shielding gases, especially with tungsten electrodes, are the following: helium, argon, neon, krypton, nitrogen, hydrogen and the like.

Reactive materials are those which will undergo physical and/or chemical changes at the temperatures of the cathode surface during operation of the arc and which are chemically active toward the cathode material. These materials may be gases or condensed phase materials entrained in gases. For example, chlorine will dissociate at high temperatures and attack the cathode material. Hence chlorine is a reactive gas. Silica is a solid material which vaporizes at high arc temperatures and which, if in contact with the cathode material, can react with it and cause cathode erosion. Silica is a reactive condensed phase material which can be entrained either in a shielding gas, or if so desired in a reactive gas, and introduced into the arc column according to this invention.

In addition to protecting the conical cathode surface against physical abrasion and chemical attack, interposing a stream of shielding gas between the cathode and the reactive material fed into the injection window in accordance with the present invention surprisingly widens the conduction column and contributes vastly to arc stability. The basis for this surprising phenomena is believed to be associated with the "plasma bubble". The plasma bubble appears as a small bright tear drop shape at the end of a conical tip cathode. It is shown, in FIG. 1, as reference 27. The temperature within the bubble is exceedingly high, generally in excess of 20,000°C., and it can serve as a very powerful generator of charge carriers. During forced connection the charge carriers are being rapidly depleted and efficient generation of new charge carriers is necessary to prevent arc instability.

In any event, the size and shape of the plasma bubble appears to be influenced by the material projected into the column via the injection window. Injection of a material into the column through the injection window enlarges the plasma bubble. (In FIGS. 2 and 3, an en-

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larged plasma bubble is shown at **28**). Introducing reactive material into the bubble, especially solids, reduces the bubble temperature and also reduces the ion generation rate. This decrease of charge carrier in the conduction zone that occurs under forced convection renders the arc unstable and ultimately extinguishes it. In contrast, when a non-reactive shielding gas is interposed between the cathode and the reactive material fed into the arc column via the injection window, the non-reactive gas enters the plasma bubble and sufficient charge carriers are generated without detrimentally effecting the arc stability. The reactive material enters the column through the injection window along a path which intersects just above the bubble. The concomitant result is a widening of the column just above the plasma bubble, thus creating additional window space. Thus, in one aspect of the present invention an apparatus is provided for the injection of two separate streams of gas. For example, in FIG. 2, two concentric annular passages are provided around the conical cathode **1** by conical shrods **4** and **5**. Annular passage **15** is provided for introduction of a stream of shielding gas, while annular passage **14** is provided for the introduction of a reactive material such as a fluid medium containing an entrained condensed phase.

It should be understood that the dimensions of the two annular orifices are such that both streams of fluids can enter the column via the contraction zone or window. The annular inlet orifice area together with the inlet gas pressures will affect the injection velocity (mass flow density). By adjusting the inlet area and gas pressure the injection velocity may be varied without altering the total mass flow (convection). Preferably the shielding gas and reactive fluid orifices are sized so that little, if any, reactive material enters the plasma bubble and instead the reactive material enters the injection window along a path which intersects just above the plasma bubble.

In FIG. 3, a stream of reactive material is introduced through a plurality of tubes shown as **16** and **16***a* arranged generally symmetrically around the cathode axis and directed via nozzles **17** and **17***a* substantially parallel to the surface of the cathode tip and into the arc column. Preferably the nozzles are directed so that reactive material will enter the window along a path which intersects above the plasma bubble. Between the flow of reactive material and the conical tip a shielding gas stream is interposed by the annular passage defined by shroud **5**.

The total mass flow of the injected fluid medium if varied at substantially a constant current level and mass flow density, will alter the shape of the contraction zone **3**. When the total mass flow or convection rate of the injected fluid medium is increased from zero, little or no change in the shape of the contraction zone **3** is observed and substantially all the injection fluid enters the arc column through the injection window. However, as the total mass flow of the injected medium is increased further, at a point depending on the material injected, the contraction zone begins to elongate, thus decreasing the space rate of contraction of the arc column diameter. This space rate of contraction may be called the window angle and is depicted in FIG. 1 as the angle α. When the angle α is sufficiently reduced, that is, to about 40° or less, the major portion of the fluid flow medium does not enter the arc column.

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By use of the aforementioned technique, many chemical and physical reactions can be conducted. For example, extremely finely divided refractory oxides, such as silica, alumina, and magnesia, can be produced by entraining particulate reactive materials in a fluid medium injecting them through injection window into the arc column, and thereafter recovering them after they leave the arc column. Protection of the cathode from the abrasive action of the entrained refractory solids as well as from chemical attack by other reactive materials makes processing of such materials in the arc commercially practical. For example, metal nitrides can be formed by reacting metal oxides in the arc with nitrogen or ammonia.

Illustrative of the apparatus and method of the present invention is the following example.

EXAMPLE

The device utilized in this example is shown diagramatically in FIG. 2. It consists of a ½ inch copper rod containing a tungsten insert 3/16 inch in diameter, in the form of a conical tip with a 45° cone angle as the cathode. Surrounding the cathode is a conical shroud **5** defining an annular passage **15**. Shroud **15** also has a cone angle of 45° so that it mates with the conical surface of the tip. Surrounding shroud **5** is a conical shroud **4** defining an annular passage **14**. Shroud **4** also has a cone angle of 45° and both shrouds **4** and **5** terminate a few millimeters behind the cathode tip **7**, thus forming annular orifices **34** and **35** respectively. Annular passage **14** is effective in directing the flow of fluid material containing a condensed phase along the conical surface of the inner shroud **5** into the arc discharge through the contraction zone. Annular passage **15** is effective in interposing a stream of shielding gas between the fluid medium in passage **15** and the cathode tip **1**.

Shrouds **4** and **5** are fabricated from copper and shroud **5** is provided with internal water cooling.

For the purpose of this experiment, various annular orifice areas were used ranging generally from about 0.005 inch to about 0.015 inch for orifice **34**, and from about 0.032 inch to 0.120 inch for orifice **35**.

The arc is ignited as follows:

1. The electrodes are brought in close proximity to each other, e.g., about 5mm. A moderate flow of shielding gas is started and introduced via annular passage **15**. The starting flow of gas is normally about 2 to about 4 grams per minute. The arc is then ignited using a momentary high frequency spark to form a conductive path between the closely spaced electrodes. With the main power supply turned on, a rapid spark to arc transition occurs.

2. Once the arc is ignited, the arc gap is increased to its desired value to withdrawing the cathode.

To start up and maintain stable operation of the arc, the following parameters have been employed:

Arc current	50 – 750 amps
Arc voltage	50 – 165 volts
Arc gap	0.3 – 1.0 centimeters (start-up) 8 – 20 centimeters (operation)
Total mass flow of inert gas	3 – 5 grams/minute (inner shroud) 0 – 10 grams/minute (outer shroud)

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3. When optimum conditions are obtained, that is, when the maximum column temperature is reached with total mass flow of the fluid medium well below the value which would reduce the angle α to less than about 40°, the condensed phase is entrained in the fluid medium and introduced into the arc via annular passage 14. The amount of material entrained is kept initially low and slowly increased until the fraction of the mass flow of dense material is comparable to that of the entraining material. The optimum mass flow rate of shielding gas introduced via passage 15 is in the range of 4 to 8 gm/min., and the mass flow of gas or fluid entraining medium introduced via passage 14 is in the range of 12 to 40 gm/min.

At the point where the mass flow of entrained material is comparable to that of the carrier fluid medium, the window angle is enlarged and may be increased further without serious loss of penetration into the column. Thus, in the Table shown below where solids such as silica were used in an argon fluid medium, significant increase in the injection rate could be sustained before any appreciable amount of feed material could be observed as being deflected from the column. At the same time the silica which otherwise would rapidly attack the cathode tip is processed without any significant destruction of the cathode.

In the Table below are listed some typical conditions under which various materials were introduced into the arc column. In these runs, argon was used as a shielding gas and as a fluid medium for entraining the solids. The arc current was 330 amps and the arc voltage was 100 volts. The measured arc gap was 3.4 inches.

TABLE

| Run | Condensed Phase | Mass Flow g/m | | | Prod.Size & Shape |
		Shielding Gas	Fluid Me-dium	Cond. Phase	
1	SiO₂	4	18	25	100–300A Spheres
2	CaO	4	18	8	100–300A Spheres
3	BaO	4	18	8	100–300A Spheres
4	Al₂O₃	4	18	8	100–300A Spheres
5	MgO	4	18	8	100–200A Cubes
6	ZnO	4	18	8	100–300A Spheres
7	FeO	4	18	8	100–300A Spheres

As can be seen from the foregoing, relatively large particles were effectively vaporized and subsequently quenched to provide submicron size particles. Thus, silica particles sized in the range of 50 to 80 microns were vaporized and quenched to give particles of 100 to 300A. in size.

What is claimed is:

1. A process for energizing fluid medium in the conduction column of a free-burning electric arc comprising: establishing an arc discharge between an anode and a cathode having a conical tip whereby a plasma bubble is formed at the cathode tip and whereby said arc discharge forms a contraction of the current-carrying area in the transition region in the vicinity of the cathode;

forcefully projecting fluid medium along the surface of said conical tip of said cathode into and through

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the contraction of the current-carrying area in the transition region in the vicinity of the cathode and along a path which intersects above the plasma bubble; and

simultaneously interposing between said fluid medium and said conical tip of said cathode in a direction parallel to the surface of said conical tip a stream of gas that is chemically inert toward the cathode material during operation.

2. The process of claim 1 wherein said fluid medium is an entrained condensed phase.

3. In the process of energizing a reactive material by means of a free-burning arc discharge between an anode and a cathode having a conical tip, wherein said arc discharge forms a contraction of the current-carrying area in the transition region in the vicinity of the cathode and wherein said reactive material is forcefully projected along the surface of said conical tip of said cathode into and through said contraction of the current-carrying area in the transition region in the vacinity of the cathode, the improvement comprising interposing between said forcefully projected reactive material and said conical tip of said cathode, in a direction parallel to the surface of said conical tip, a stream of shielding gas whereby said tip of said cathode is substantially protected from contact with said reactive material.

4. The process of claim 3 wherein said shielding gas is selected from the group consisting of helium, argon, neon, krypton, xenon, nitrogen and hydrogen.

5. The process of claim 3 wherein said reactive material is a gas.

6. The process of claim 3 wherein said reactive material is an entrained condensed phase.

7. The process of claim 6 wherein the entrained condensed phase is a solid.

8. The process of claim 6 wherein said entrained condensed phase is a liquid.

9. Apparatus for energizing material in an arc column comprising:
    a. an anode and a cathode having a conical tip;
    b. means for providing a free-burning arc discharge between said anode and said cathode whereby said arc discharge forms a plasma bubble and a contraction in the current-carrying area in the transition region in the vicinity of the cathode;
    c. directing means for projecting a reactive material substantially parallel to the surface of the conical tip of said cathode into said contraction of the current-carrying area; and
    d. a conical shroud forming an annular passage for admitting a stream of shielding gas in a direction substantially parallel to the surface of the conical tip of said cathode and between said tip and said reactive material.

10. The apparatus of claim 9 wherein said means for directing said reactive material into the contraction zone directs said reactive material along a path which intersects above the plasma bubble.

11. The apparatus of claim 10 wherein said means for directing said reactive material includes a second conical shroud defining an annular passage around said annular passage serving as a conduit for shielding gas.

12. The apparatus of claim 10 wherein said means for directing said reactive material includes a plurality of nozzles spaced around the periphery of said cathode tip to deliver a stream of reactive material substantially parallel with said tip.

13. The apparatus of claim 12 wherein at least four nozzles are spaced around said cathode.

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