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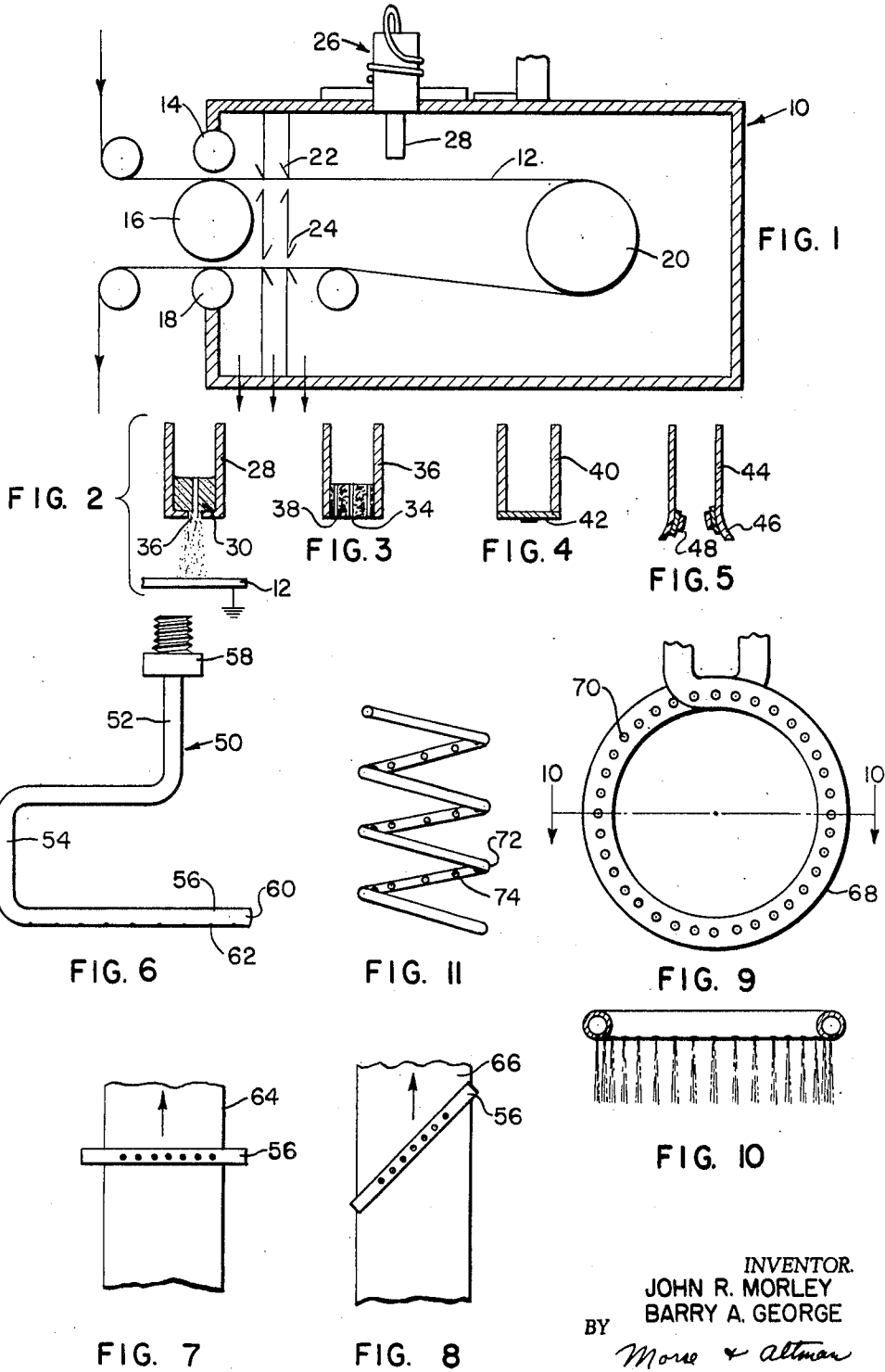
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3,210,518

HOLLOW CATHODE DEVICE

Filed Dec. 21, 1962

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

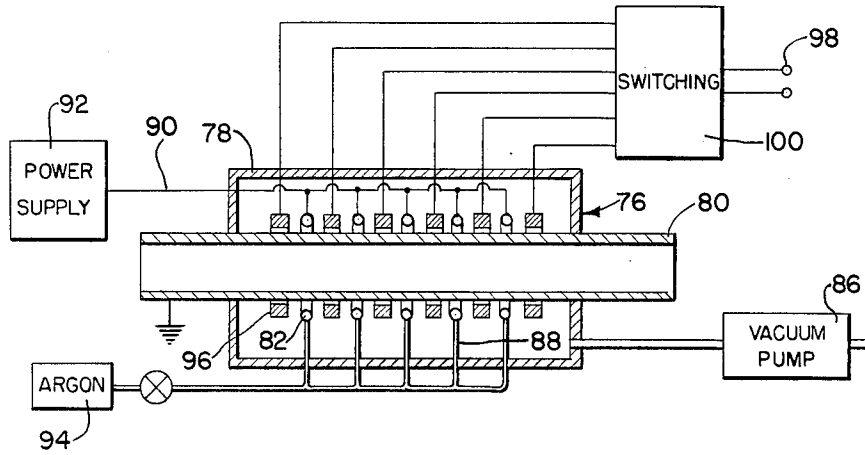


FIG. 12

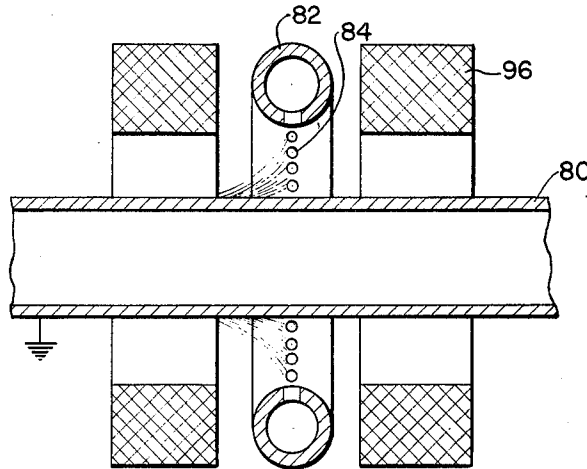


FIG. 13

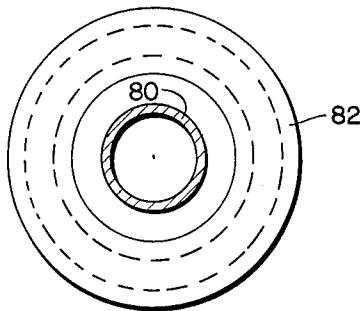


FIG. 14

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3,210,518

## HOLLOW CATHODE DEVICE

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tion, Cambridge, Mass., a corporation of Delaware  
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This invention relates generally to electron beam heating devices and more particularly concerns a new and improved hollow cathode discharge device for use in generating a plasma source from which an electron beam may be extracted and accelerated towards a workpiece.

In my co-pending U.S. application Serial No. 196,041, there is disclosed a high-temperature apparatus employing a hollow cathode through which flows a stream of inert gas. The cathode is connected to an electrical power source whereby the cathode may be heated to a level sufficient to ionize the gas flowing through it. The electrons developed in the resulting plasma are then extracted by a D.C. potential, and focused by electromagnet coils onto a workpiece spaced from the cathode and maintained at a ground potential. It has been found that this system is extremely useful in various high temperature applications such as annealing and melting of refractory materials, for example.

The hollow cathode electron beam gun assembly has been found to be particularly satisfactory by reason of the fact that it is efficient and may be manufactured at a substantially lower cost than conventional electron beam guns previously available. However, even the cathode disclosed in the above application displays an efficiency of only 60% or so. Moreover, existing electron beam devices, by reason of the configuration of the electron beam, generally lack flexibility of operation. This is primarily due to limitations inherent in the cathode assembly. Heretofore, electron beams could be produced only in conventional shapes such as cones, columns and such other shapes as could be conveniently manipulated by the focusing coils.

Accordingly, it is an object of the present invention to provide improvements in electron beam heating devices.

Another object of this invention is to provide improvements in cathodes for electron beam heating devices employing ionized gases as a source of electrons.

Still another object of this invention is to raise the efficiency of electron generation.

A further object of this invention is to provide a hollow cathode for electron generation which cathode may be readily shaped into various configurations best suited for particular applications.

Yet another object of this invention is to provide a novel continuous control atmospheric furnace for annealing, heat treating, brazing and the like.

More particularly, this invention features a cathode element for use in generating a plasma for an electron beam gun wherein the cathode has a tubular configuration with one or more restricted discharge orifices formed in the walls thereof. The cathode is located in spaced relation to the workpiece which is at ground potential. Upon heating of the cathode and the introduction of an inert gas to the interior thereof, a high temperature plasma will be formed in the zone adjacent the discharge ports. A D.C. potential between the cathode and the workpiece will extract the electrons from the plasma and accelerate them towards the workpiece thereby raising the temperature of the workpiece. A magnetic field generated by the focus coils contains the electron beam to any desired angular divergence. It has been found that by restricting the discharge orifice in the cathode, a much higher efficiency is obtained for reasons that will presently appear. This invention also features a tubular cathode closed at one end and having a series of discharge ports spaced in a se-

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lected pattern along the length thereof. The cathode element may be formed into any one of a variety of configurations to provide electron beams of various shapes such as circles, spirals, strips and other useful forms.

The cathode which provides an elongated strip beam is particularly useful for annealing strip material and is a feature of this invention. As another feature, the cathode is mounted for angular movement relative to the workpiece for adjustment to the most efficient operating position.

This invention also includes a novel atmospheric furnace employing a plurality of hollow cathode elements in association with a plurality of electro-magnetic coils connected to suitable switching means for sweeping in an oscillatory manner the discharge from the cathodes over the surface of the furnace heating wall.

But these and other features of the invention, along with further objects and advantages thereof, will become more fully apparent from the following detailed description of preferred embodiments thereof, with reference being made to the accompanying drawings in which;

FIG. 1 is a sectional view in side elevation, somewhat schematic, of a high temperature strip annealing furnace embodying a cathode assembly made according to the invention,

FIG. 2 is a detailed sectional view in side elevation of a hollow cathode made according to the invention,

FIGS. 3, 4 and 5 are views similar to FIG. 2 but showing modifications thereof,

FIG. 6 is a side elevation of a hollow cathode device for use particularly in strip annealing,

FIG. 7 is a top-plan view, somewhat schematic, showing the cathode of FIG. 6 assembled over a strip of material being annealed,

FIG. 8 is a view similar to FIG. 7 but showing the cathode assembly rotated into a diagonal position relative to the work,

FIG. 9 is a bottom plan view of an annular hollow cathode made according to the invention,

FIG. 10 is a cross-sectional view taken along the line 10—10 of FIG. 9,

FIG. 11 is a view in side elevation of a spiral shaped cathode made according to the invention,

FIG. 12 is a sectional view in side elevation somewhat schematic of a high temperature atmospheric furnace made according to the invention,

FIG. 13 is a detail sectional view of the furnace shown in FIG. 12, and,

FIG. 14 is an end view of the device shown in FIG. 13.

Referring now to the drawings and FIG. 1 in particular, the reference character 10 generally indicates a sealed housing or vacuum chamber for use in annealing strip material 12. In practice, the chamber is evacuated to a level of  $10^{-2}$  to  $10^{-4}$  torr while the strip material 12 is fed continuously into the chamber through sealing rolls 14, 16 and 18 and looped over a water cooled roll 20. Inner wiper seals 22 and 24 may be provided to maintain the low pressure level within the housing 10.

Mounted on top of the housing 10 and directed to the interior of the chamber is a hollow cathode electron beam gun, indicated generally by the reference character 26. The gun includes a cathode 28 which is directed against the strip material 12. The strip material 12 is, of course, maintained at ground potential with respect to the cathode and, in the illustrated device, the cathode 28 has a hollow, tubular configuration which is shown best in FIG. 2. In practice, a supply of an inert gas, such as argon, or the like, is fed through the tubular cathode 28 which is electrically connected to a source of high frequency current. The gas is delivered through the conduit to the ionizing zone at a controlled rate of flow which may range from

$\frac{1}{40}$  to 50 ATM cc./min., for example. Sufficient current is supplied to heat the cathode to thermionic emission thereby ionizing the gas at the discharge end of the cathode. Focusing coils are provided to focus the electrons drawn from the plasma and are accelerated towards the strip material 12 by a D.C. potential. Once the discharge becomes self-sustaining, the RF current may be removed and a D.C. potential of perhaps 30 to 50 volts is maintained between the cathode and the anode.

In my co-pending U.S. application 196,041, the cathode for the gun was an open ended tubular unit which was satisfactory in generating a plasma and directing electrons against the anode. However, it has now been found that the efficiency of the gun may be increased substantially by restricting the size of the discharge orifice in the manner best shown in FIGS. 2 to 5. Typically, the cathode is fabricated from a relatively thin-walled tube of high temperature material such as tantalum 28 and has a plug 30 mounted at the discharge end with a small orifice 36 formed therein. The argon gas is fed down through the tube and discharges through the orifice 36 in a fine jet expanding into the vacuum chamber 10. The chamber is continuously pumped to maintain a background pressure between  $10^{-2}$  and  $10^{-4}$  torr. Locally around the orifice 36, the gas pressure is very much higher and thus there is a large pressure gradient in front of the cathode 28. This local high pressure region is converted into a plasma by coupling the RF power to the gas to bring about its ionization. At the onset of the plasma production by the RF excitation of the gas, electrons are drawn from the plasma region around the cathode and are accelerated through a small voltage to the anode or workpiece which in this case is the strip 12. Since plasmas are essentially neutral in total charge, removal of the electrons will tend to leave the plasma with an excess of positive ions. These excess ions will be accelerated towards the cathode through 14.4 volts, the first ionization potential for argon. The power received by the cathode will be the product of this voltage and the ion current. This power is sufficient to raise the temperature of the cathode to a white heat and electrons are given off thermionically according to Richardson's law. These electrons in turn can carry out further ionization of the gas and are also accelerated to the anode directly.

With the cathode heated to thermionic emission, the discharge becomes self-maintaining and the RF power may be deenergized. The discharge is very stable over a considerable range of gas flow and background pressure, but has a small specific power density. Under such conditions, the density of the discharge tends typically to follow the pattern of a small jet of gas flowing through an orifice into a reduced pressure zone. Concentration of the electron discharge is easily achieved through the use of magnetic focusing and the beam can be brought down to a size smaller than the cathode diameter. The electrons have an unusually low velocity for an electron beam in a vacuum which is used for heating purposes, but because of this, small magnetic fields are adequate for producing a well-focused beam. The magnetically confined beam is in a form of an intense blue column for argon gas, extending all the way from the cathodes to the anode.

A typical set of operating conditions for a half-inch thin-walled tantalum tube with no orifice restriction would be 500 amperes of current at a potential of 30 volts. Of this 15 kw. of power, approximately 65% is received at the anode or workpiece. In other words, approximately  $\frac{1}{3}$  of the available power is returned to the cathode. By employing the cathode described above, however, the efficiency could be raised to 75 to 80%. This raise in efficiency arises from the utilization of the returning argon positive ions to heat the constricted end of the cathode over a much smaller area than heretofore. This

raises the temperature of the cathode tip and causes more thermionic emission to occur.

As an added advantage with a hollow cathode having a restricted orifice such as shown in FIG. 2, the plasma is contained in smaller portion of the tube than in the case with other cathodes. With a hollow cathode having a fully open end, a large part of cathode assembly must be heated to thermionic emission before the required plasma is produced. Now, however, only that portion immediately adjacent to the restricted orifice need be heated. This portion is approximately 25% of the total length of the cathode. This, of course, reduces the amount of energy required to heat the cathode to thermionic emission and results in a substantial savings since there is no waste of electrical power.

In FIGS. 3 to 5, there are illustrated several modifications of the cathode shown in FIG. 1. In FIG. 3, for example, in place of the plug 30 a wad 34 of metallic fibers has been used to plug the end of a hollow cathode 36. Typically, the wad 34 has a number of small openings 38 drilled therethrough in an axial direction to facilitate the discharge of the gas. The increase of surface area provided by the wad 34 increases the emission area of the cathode and adds to the efficiency of the apparatus. In FIG. 4 there is illustrated a cathode 40 at the end of which is mounted a porous tungsten cap 42 preferably fabricated by a sintering process. Here again, the efficiency of the apparatus is improved by the use of a large thermionic emissive surface area combined with a small gas flow. In FIG. 5 a hollow cathode 44 is formed with a flared end portion 46. At the flared discharge end of the cathode a number of tapered annular inserts 48 are mounted to restrict the gas flow and to increase the surface area around the plasma region.

Referring now more particularly to FIG. 6 of the drawings, there is illustrated a hollow cathode element 50 made according to the invention and particularly well adapted for use in strip annealing operations. As shown, the cathode 50 is formed from an elongated tubing of some suitable material such as tantalum or the like and has a vertical leg portion 52, a U shaped end portion 54 and a horizontal leg portion 56. The upper end of the vertical leg 52 is connected to a rotatable coupling member 58 while the free end of the horizontal leg 56 is closed by a cap 60 or other means. Formed in a line along the lower wall of the leg portion 56 is a series of restricted orifices 62 through which a like number of separate electron beams are emitted in parallel relation to one another. The several beams combine to form a curtain shaped beam which, when directed toward a flat workpiece such as a strip 64, produces an elongated track across the strip 64 as suggested in FIG. 7. The several beams discharging from the orifices 62 impinge on the strip 64 and overlap to some extent to give a continuous electron beam across the strip. As the strip advances in the direction of the arrow, it will be heated and annealed uniformly across its entire width.

By mounting the cathode 50 to a rotatable coupling, it is possible to change the angle of the leg portion 56 in relation to the strip 64. This feature becomes useful when annealing strips of goods that are less than the effective width of the leg portion 56. For example, in FIG. 7 the strip 64 is substantially the same width as the leg 56 so that the leg 56 will be arranged at a right angle with respect to length of the strip 64. However, in FIG. 8 a narrower strip 66 is being annealed and, in this instance, the cathode has been rotated so that all of the orifices 62 will be used effectively against the strip 66. Otherwise, a substantial portion of the power output would be wasted. By being able to rotate the cathode in this fashion, it is possible to maintain the same power output when changing from strips of different widths by increasing the travel speed of the strip. Also, there is no need to change cathode elements to accommodate strips of different dimensions.

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In FIGS 9 and 10 there is illustrated a further modification of the invention and in this embodiment a tubular cathode 68 has been formed into an annular configuration for use in annealing rings and other shapes where an electron beam of annular configuration is required. As shown, the cathode 68 is formed from a tube of tantalum, or the like, with one end plugged and the other end connected to a source of inert gas such as argon. The annular portion of the cathode is formed with a series of spaced orifices 70 arranged concentrically about the cathode and oriented in an axial direction.

In FIG. 11 there is illustrated yet another modification of the invention and in this embodiment a cathode 72 is formed as a spirally wound tubing closed at one end and provided with a series of spaced orifices 74 all directed radially inward. A cathode of this configuration would be useful in such applications as drip melting or annealing of rods passed axially through the cathode. As before, a flow of inert gas such as argon is delivered through the tubing and ionized in the zone adjacent the orifices.

Referring now more particularly to FIGS. 12 and 14, there is illustrated a high temperature atmospheric furnace 76 comprising a hermetically sealed vacuum chamber 78 through which extends a tubular member 80 which is sealed against the chamber 78 and is adapted to receive various specimens such as those commonly introduced to high temperature furnaces. Preferably, the tubular member 80 is fabricated from a metallic refractory material and is maintained at ground potential with respect to a series of annular cathodes 82. The cathodes 82 are of a configuration similar to the cathode illustrated in FIGS. 9 and 10 with the exception that the restricted orifices 84 are directed radially inwards as best shown in FIG. 14. The vacuum chamber 76 is connected to a vacuum pump 86 which maintains the chamber a constant level of  $10^{-2}$  or  $10^{-4}$  torr. Each of the cathodes 82 is supplied with a flow of inert gas such as argon by conduits 88 connected to a source 94. Each cathode 82 is connected to an electrical power supply 92 by leads 90 whereby the cathodes may be heated to produce a plasma within the hollow interior of the several cathodes. The tubular member 80, being at ground potential, will attract the free electrons from the plasma and thereby cause the tubular member to be heated. The tubular member 80, being subjected to a plurality of radial electron beams spaced along its length will be extremely hot and will subject any specimen placed inside the member 80 to extreme heat.

In order to provide uniformity of heating over the outer surface of the tubular member 80, means are provided for sweeping the several radial electron beams back and forth along the surface of the member 80 in an oscillatory fashion. According to the invention, a number of electro-magnetic coils 96, coaxial with the member 80 and the cathodes 82, are positioned between the cathodes along the length of the member 80 as best shown in FIG. 12. Each of the coils 96 is connected to a power source 98 through a switching device 100. It will be understood that upon energization of one of these coils the magnetic force field developed by the coil will draw the several radial electronic beams axially along the outer surface of the member 80 as suggested in FIG. 13. By alternately energizing a coil on one side of the cathode and deenergizing it and then energizing the coil on the opposite side of the cathode, the electron beams will be made to sweep back and forth along the outer surface of the member 80 thereby providing uniform heating of that member.

While the invention has been described with particular reference to the illustrated embodiments, it will be understood that numerous modifications thereto will appear to those skilled in the art. Accordingly, it will also be understood that the above description and accompanying drawing should be taken as illustrative of the invention and not in a limiting sense.

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Having thus described the invention, what is claimed and desired to be obtained by Letters Patent of the United States is:

1. A cathode for an electron beam gun assembly, comprising an elongated tubular body of refractory material, conduit means connected to said body for delivering a flow of inert gas through said body, said body being formed with a plurality of discharge orifices of restricted size, A.C. means connected to said body for electrically energizing said body to thermionic emission for ionizing said gas to produce low pressure plasma, and D.C. means for extracting free electrons from said plasma and focusing them on a workpiece.

2. A cathode according to claim 1 wherein said body is formed with a straight leg portion movably mounted for rotation through a plane generally parallel with the plane of the workpiece and said orifices are arranged in spaced linear alignment along the length of said leg portion.

3. A cathode according to claim 1 wherein said body is formed with an annular portion and said orifices are arranged in spaced relation thereabouts.

4. A cathode according to claim 1 wherein said body is formed with a spiral portion and said orifices are arranged in spaced relation to one another and directed radially inwards.

5. A high temperature furnace, comprising a sealed housing, a tubular metallic member sealed against and passing into said housing and adapted to receive a specimen therein, means for evacuating said housing, at least one tubular cathode extending about said member in spaced relation to the outer surface thereof, said cathode being formed with a plurality of restricted orifices disposed oppositely to said member, means for delivering a flow of inert gas into the interior of said cathode, electrical means connecting said cathode for energizing said cathode to a state of thermionic emission and thereby ionizing said gas to produce a low pressure plasma, means for maintaining said tubular member at positive potential with respect to said cathode whereby the free electrons from said plasma will be attracted in beams to said member, electro-magnetic induction means disposed on opposite sides of said cathode and adapted to displace said beams when energized and switching means for energizing and deenergizing alternate ones of said induction means for sweeping said beams back and forth over the surface of said member.

6. A high temperature furnace, comprising a sealed housing, a tubular metallic member sealed against and passing into said housing and adapted to receive a specimen therein, means for evacuating said housing, a plurality of axially spaced tubular cathodes extending about said member in spaced relation to the outer surface thereof, said cathodes being formed with a plurality of restricted orifices disposed oppositely to said member, means for delivering a flow of inert gas into the interiors of said cathodes, electrical means connecting said cathodes for energizing said cathodes to a state of thermionic emission and thereby ionizing said gas to produce a low pressure plasma, means for maintaining said tubular member at positive potential with respect to said cathodes whereby the free electrons from said plasma gas will be attracted in beams to said member, electromagnetic beam-displacing induction means disposed on opposite sides of each of said cathodes and switching means for energizing and deenergizing alternate ones of said induction means for sweeping said beams back and forth over the surface of said member.

7. An electron beam gun assembly, comprising a tubular body of refractory metal constituting the cathode for said assembly, conduit means connecting said body for delivering a flow of inert gas through said body, said body being formed with at least one discharge orifice, said orifice having a cross-sectional area less than the

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cross-sectional area of said cathode, A.C. means for initially ionizing the inert gas and for electrically energizing the tip of the cathode body to thermionic emission for further ionizing said gas to a low pressure plasma, D.C. means for extracting free electrons from said plasma and directing said electrons toward a workpiece, a foraminous wad of metallic fibers lodged in the discharge end thereof and means for magnetically focusing said electrons into a beam configuration.

8. An electron beam gun assembly, comprising a tubular body of refractory metal constituting the cathode for said assembly, conduit means connecting said body for delivering a flow of inert gas through said body, said body being formed with at least one discharge orifice, said orifice having a cross-sectional area less than the cross-sectional area of said cathode, A.C. means for initially ionizing the inert gas and for electrically energizing the tip of the cathode body to thermionic emission for further ionizing said gas to a low pressure plasma, D.C. means for extracting free electrons from said plasma and directing said electrons toward a work piece, a porous metallic end plug mounted across the discharge end of said body and means for magnetically focusing said electrons into a beam configuration.

9. An electron beam gun assembly, comprising a tubular body of refractory metal constituting the cathode for said assembly, conduit means connecting said body for delivering a flow of inert gas through said body, said body being formed with at least one orifice, said orifice having a cross-sectional area less than the cross-sectional area of said cathode, A.C. means for initially ionizing the inert gas and for electrically energizing the tip of the cathode body to thermionic emission for further ionizing said gas to a low pressure plasma, D.C. means for extracting free electrons from said plasma and directing said electrons toward a workpiece, a series of concentric annular elements mounted in the discharge end of said body and means for magnetically focusing said electrons into a beam configuration.

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10. An electron beam gun assembly, comprising a tubular body of refractory material, a workpiece spaced from said body, conduit means for delivering a flow of gas through said body, said body being formed with at least one discharge orifice opposite to the workpiece, A.C. means connected to said body for energizing said body to thermionic emission and thereby ionize said gas within said body, a wad of metallic fibers lodged in said orifice to reduce the cross-sectional area thereof and D.C. means for extracting electrons from said ionized gas and directing them to said workpiece.

11. An electron beam gun assembly, comprising a tubular body of refractory material, a workpiece spaced from said body, conduit means for delivering a flow of gas through said body, said body being formed with at least one discharge orifice opposite to the workpiece, A.C. means connected to said body for energizing said body to thermionic emission and thereby ionize said gas within said body, said body being provided with a porous metallic end plug mounted across the orifice to reduce the cross-sectional area thereof and D.C. means for extracting electrons from said ionized gas and directing them to said workpiece.

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