219-121 SR

MTR04 XR 3,655,902

United States Patent

Firestone et al.

[15] 3,655,902

[45] Apr. 11, 1972

[54] HEATING SYSTEM FOR ELECTRON BEAM FURNACE

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[22] Filed: **Oct. 19, 1970**

[21] Appl. No.: **81,720**

[52] **U.S. Cl.** ....**13/31**, 219/121 EB

[51] **Int. Cl.** **H05b 7/00**

[58] **Field of Search**............13/31; 219/121 EB; 250/49.5 D, 250/41.93 ME

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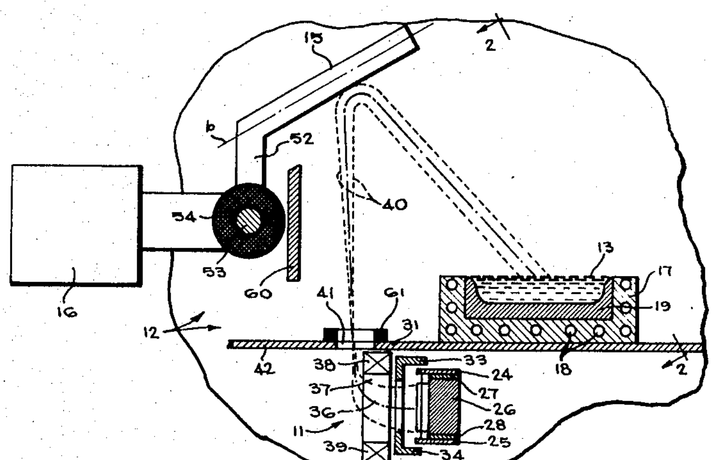
[57] **ABSTRACT**

An electron beam furnace heating system is described wherein an electron beam produced by an electron gun is directed to a target by a transverse magnetic field in the path of the beam. The field is established by a pair of bar-shaped pole pieces having their longitudinal axes in a common plane and the field of sufficient strength that the beam is deflected to emerge from the same side of the magnetic field as the side from which it enters.

9 Claims, 4 Drawing Figures



Patented April 11, 1972 **3,655,902**

FIG. 1

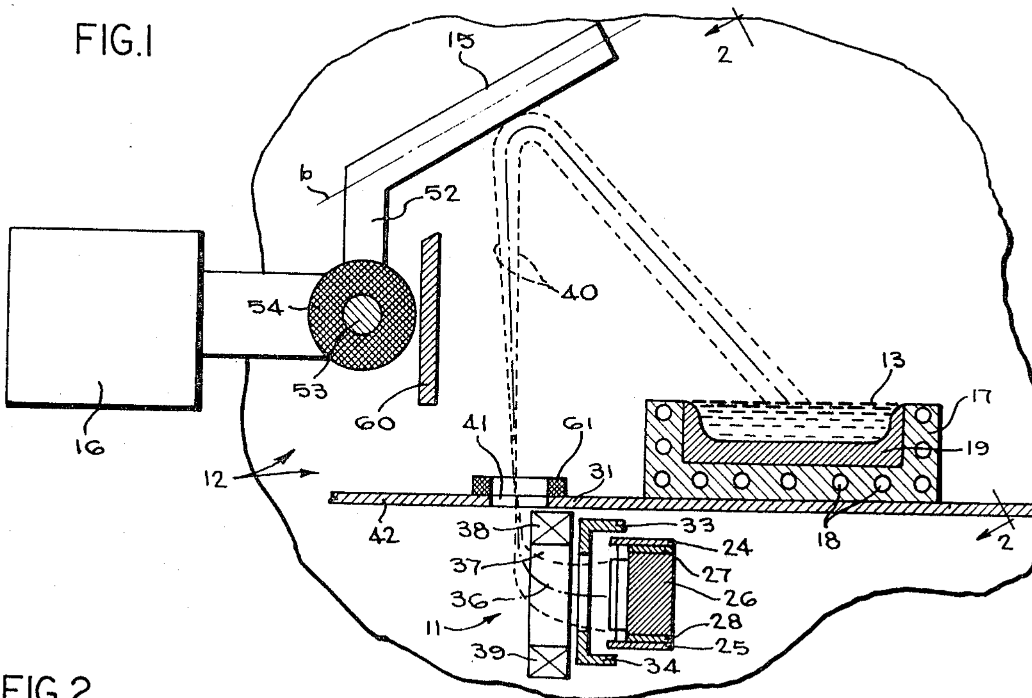


FIG. 2

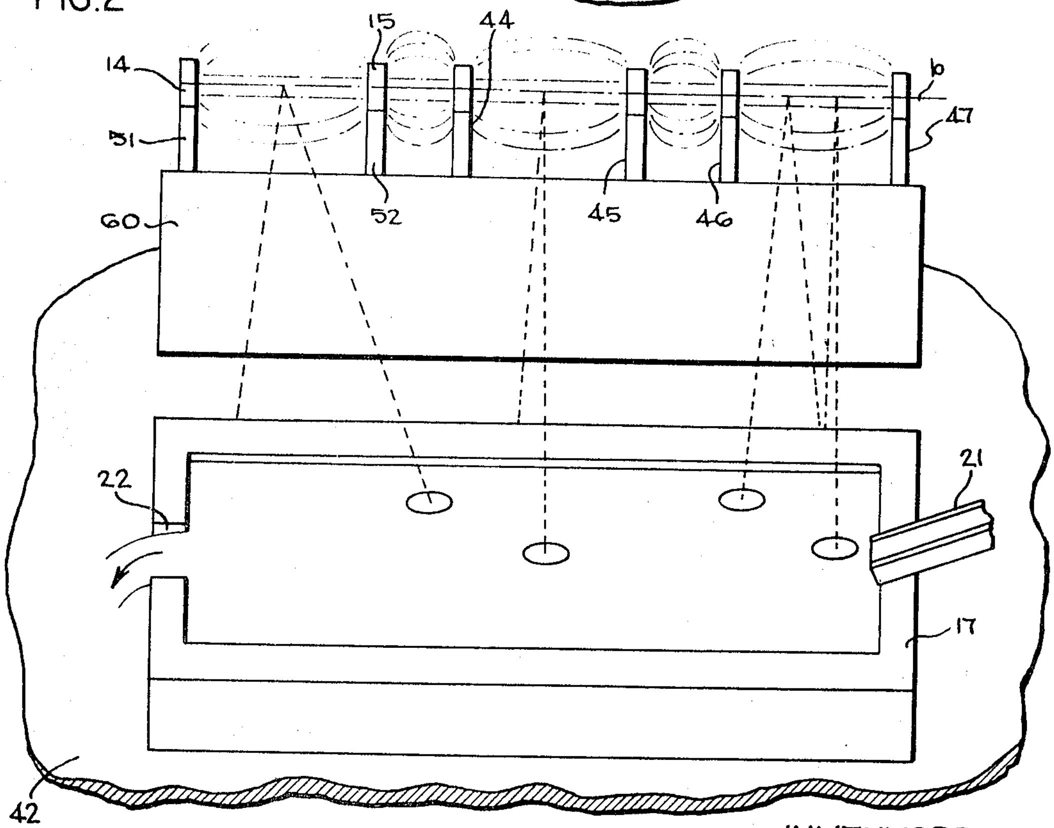


FIG. 3

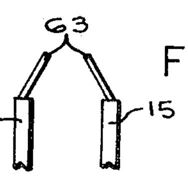
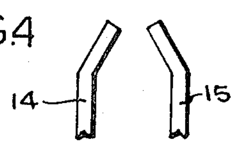


FIG. 4



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HEATING SYSTEM FOR ELECTRON BEAM FURNACE

This invention relates generally to electron beam furnaces and, more particularly, to an improved heating system in such a furnace.

Electron beam furnaces of a variety of designs are useful in the processing of many metals, alloys or other materials, for example where high standards of purity are to be achieved by outgassing or by avoiding reaction with oxygen and nitrogen, or where a substrate is to be coated by vaporization and condensation of the material. Electron beams are a particularly useful form of heating in that it is possible to inject heat into a melt locally. Electron beam furnaces typically include an evacuated enclosure, a heating system comprising one or more electron beam guns with associated deflection means for directing and focusing the beams, and a container for the molten material being processed.

Depending upon the particular type of processing being carried out, the container for the molten material may take a variety of forms. In a situation where it is desired to evaporate the material in the container and subsequently condense the material on a suitably supported substrate to coat the substrate, a typical container consists of an open topped upright crucible. Electron beam heating enables the crucible itself to be cooled and thereby form a skull of solidified molten material between the crucible and the molten material. This protects the purity of the molten material and makes it unnecessary to use high temperature refractories for the crucible construction.

Another type of processing is the purification of metals and alloys by passing the molten material or alloy over a shallow hearth. Exposure to the vacuum with coincident electron beam heating of the surface causes many volatile impurities and occluded gases to be drawn off of the molten material and thereby produces a greatly purified product.

Other forms of containers which may be utilized in metal processing include tundishes, launders, and ladles for transferring molten material between various points. Electron beam heating may be utilized to maintain the material in a molten condition while in such containers.

During the processing of molten material in an electron beam furnace, vaporized material may present ionization problems or may coat the various parts of the electron beam gun, impairing its operation. Moreover, spalling of condensed materials from cool surfaces of the vacuum enclosure, and splashing and splattering of the molten material from the crucible, may also impair operation of the electron beam gun. By positioning the electron beam gun underneath the container of the molten material and by utilizing transverse magnetic fields for deflecting the electron beam through a curving path of 180° or more, contamination and shorting of the electron beam gun is minimized.

The heating of large surface areas in electron beam furnaces may be accomplished by employing a large number of electron beam guns with separate deflecting fields for each of the beams. If the furnace enclosure is relatively large, this may present no significant problem. However, if space is at a premium, the positioning of means for establishing transverse magnetic fields closely adjacent each other may be extremely difficult due to mutual interference and distortion of the fields.

During the processing of molten material in an electron beam furnace, as well as during the vaporization thereof, a considerable amount of vaporous material may be generated. The amount of such material is typically at its maximum in the region directly above the molten target. Accordingly, it is undesirable to position means for establishing transverse magnetic fields for deflecting the beam directly above the molten target. This is because the pole pieces or other means utilized to establish the fields are susceptible of becoming heavily coated with condensed vaporous material with the possibility of a consequent adverse effect on the configuration of the magnetic field. Moreover, flaking off of such condensate may result in recontamination of the melt.

When pole pieces or other means for producing a transverse magnetic field for deflecting an electron beam are positioned off to one side of the region above the molten target, the condensation problem mentioned above is lessened. Nevertheless, several factors limit the distance from the target material at which the deflecting means can be positioned. With too low an angle of incidence of the electron beam onto the target, surface structures adjacent the sides of the target surface, such as magnetic shields or structural members, may block the path of the beam. In addition, with a very low angle of incidence, the impact area on the surface of the target is spread out, resulting in a more inefficient transfer of heat.

Accordingly, it is an object of this invention to provide an improved electron beam furnace heating system.

Another object of the invention is to provide an improved heating system for use in an electron beam furnace in which efficient use is made of space and power.

Another object of the invention is to provide an electron beam furnace heating system of minimal complexity in which a plurality of electron beams may be directed and controlled through a curving path to a target.

It is another object of the invention to provide an electron beam furnace heating system which is particularly useful for heating large areas of molten material.

Other objects of the invention will become apparent to those skilled in the art from the following description, taken in connection with the accompanying drawings wherein:

FIG. 1 is a full section side view schematically illustrating a heating system constructed in accordance with the invention;

FIG. 2 is a view taken along the line 2—2 of FIG. 1; and

FIGS. 3 and 4 are plan views of alternate configurations for pole pieces in the heating system of FIGS. 1 and 2.

Very generally, the electron beam furnace heating system of the invention comprises an electron beam gun 11 for producing an electron beam. Means 12 are provided for directing the beam to a target 13. The directing means include a pair of bar-shaped pole pieces 14 and 15 having their longitudinal axes in a common plane and positioned to produce a transverse magnetic field in the path of the beam. Means 16 are provided for energizing the pole pieces to produce a magnetic field of sufficient strength that the electron beam is deflected to emerge from the same side of the magnetic field as the side from which it enters. The field is also of sufficient strength to prevent the electron beam from penetrating past a plane extending through the longitudinal axes of the pole pieces.

Referring now to FIG. 1, one embodiment of the invention is illustrated. The electron beam furnace includes an evacuated enclosure, part of which is shown at 20. The molten material target 13 is contained in an elongated container 17 which is cooled by circulating coolant in passages 18 to form a layer or skull 19 of solidified material between the molten material and the container walls. The container 17 is illustrated as a hearth into which molten metal flows from a launder 21 (FIG. 2) at one end. The contents of the hearth are discharged at the other end through an opening 22 (FIG. 2), and the level of molten material in the hearth may be controlled by a weir, not shown. Other means for placing molten material in the hearth and removing it therefrom may include such things as tundishes, siphons, or ladles. Between entry and exit, the material flows slowly along the hearth and thereby has a very high exposure rate to the vacuum environment in which the illustrated apparatus is disposed.

The hearth type of arrangement illustrated provides a large surface area of molten material with shallow depth for long times of exposure of the molten material to the vacuum. Such an arrangement is particularly useful in the purification of many types of steel and nickel base alloys as well as most of the refractory metals, such as columbium, tantalum, titanium, zirconium and others. Experiments have shown that many purification reactions that involve differential vaporization phenomena or other types of outgassing require residence times of many tens of seconds with the molten surface exposed to very low pressures. In such instances the illustrated configuration, that of a long linear hearth with the molten material flowing slowly along it, is particularly advantageous. Electron beams are utilized to prevent solidification of the material on the hearth as the material flows along the hearth, and to provide localized regions of high heat to vaporize impurities and produce thermal stirring.

In the illustrated apparatus, a plurality of electron beams are utilized to provide heating of the target molten material 13 in the hearth 17. The electron beams are produced by a plurality of similar electron beam guns, only one of which (11) is shown, distributed along and underneath the hearth 17 at spaced intervals.

The electron beam guns may be of any suitable type. A preferred form, however, is that shown and described in U.S. Pat. No. 3,514,656 assigned to the assignee of the present invention. The details of such a gun are shown in connection with the gun 11 in FIG. 1. It is to be understood that the other guns may be of identical construction.

Referring now to FIG. 1, the electron beam gun 11 includes an elongated emitter 23 for producing electrons. The emitter is preferably a tungsten wire and extends between the supporting members 24 and 25. Means, not illustrated, provide a direct current potential across the members 24 and 25, resulting in a flow of direct current through the emitter 23. The current flow raises the temperature of the emitter causing it to produce free electrons.

The free electrons produced by the emitter 23 are reflected on three sides by a shaping electrode 26. The electrode 26 is insulated from the emitter support members 24 and 25 by insulating strips 27 and 28, respectively. The shaping electrode 26 is formed with an elongated recess 29 through which the emitter 23 extends. When the shaping electrode is maintained at the emitter potential, by suitable connection not illustrated, the electrons produced by the emitter 23 tend to move out of the open end of the recess 29 and away from the shaping electrode 26.

The electrons leaving the recess 29 in the shaping electrode 26 are accelerated into a beam by an accelerating electrode 31 and pass through an opening 32 therein. The accelerating electrode 31 consists of a plate with two right angle extensions 33 and 34 thereon which are attached to suitable mounting means, not illustrated. The plate 31 is maintained at a potential which is substantially more positive than the potential of the emitter and the backing electrode to produce an acceleration of the electrons. The result is a ribbon beam, that is, an electron beam having an elongated cross section which is ideally a narrow rectangle but which approximates a narrow oval. The beam has a major axis plane which extends through the emitter.

The electrons in the beam leave the emitter 23 at an acute angle in the major axis plane. The axis of the beam is indicated by the dash-dot line 36, which represents the center of the ribbon beam. A non-normal orientation of the initial electron path with respect to the emitter 23 is caused by the high intensity circumferential field produced by d-c heating current passing through the emitter. After leaving the anode opening 32, the electron beam 36 is deflected about 90° through a curved path by means of a transverse magnetic field. The transverse magnetic field is established in the initial path of the beam between a pair of elongated bar-shaped pole pieces 37, only one of which is illustrated. The pole pieces extend generally parallel with the emitter 23 and each other and are positioned on either side of the beam 36 parallel with its major axis plane. A magnet 38 extends between the upper ends of the pole pieces 37, and a magnet 39 extends between the lower ends of the pole pieces 37. The two magnets are identically oriented with regard to their polarities, and are electromagnets connected to a suitable control circuit and power supply, not shown. The polarities are established with field lines running perpendicularly into the plane of the paper as illustrated in the drawing, thereby causing an upward deflection of the electron beam 36 as illustrated. The effect of the field on the electron beam also produces a convergence of the opposite edges of the beam, as shown by the dotted lines 40, toward each other in the plane of the curving path due to a longer path length of electrons toward the lower edge of the beam in the magnetic field established by the pole pieces 37. The details of the deflecting and focusing of the beam are set out more fully in the aforementioned patent.

After leaving the electron beam gun 11 and after being deflected upwardly through a change in direction of about 90°, the electron beam is passed through an opening 41 in a vapor barrier 42. Although the vapor barrier 42 may not always be necessary, in situations where a large quantity of vaporous material is produced, the vapor barrier 42 provides additional protection for the electron beam gun 11. In addition to the vapor barrier 42, a separate pumping system (not shown) may be provided in the lower region of the furnace interior to thereby maintain the electron beam gun 11 in a substantially vapor-free environment. This enhances the life of the emitter of the electron beam gun and improves the quality of the beam as it enters the upper part of the furnace chamber.

In order to deflect the beam from its generally vertically upward path in the upper part of the furnace chamber back down onto the surface of the target 13, the pole pieces 14 and 15 are provided. Similar pairs of pole pieces 44, 45 and 46, 47 are provided for deflecting the electron beams produced by the other guns, as may be seen in FIG. 2. As previously mentioned, the electron beam is deflected back down onto the molten material in the hearth at an angle which is preferably between about 30° and 60° from the vertical. An angle greater than 60° with respect to the vertical generally results in a beam spot which is too spread out and, in addition, the beam may be interfered with by structures along the sides of the hearth. An incident angle of less than 30° with respect to the vertical may necessitate the positioning of the pole pieces too close to the region directly above the hearth, where the tendency for condensate to collect on the pole pieces is undesirably high.

The pole pieces 14 and 15 are energized to provide a magnetic field which extends transversely of the electron beam above the opening 41 through which the beam emerges and passes upwardly into the upper part of the electron beam furnace chamber. The field includes a portion of substantially uniform strength in the region directly between the pole pieces. The field also includes upper and lower fringe regions where the lines of flux flow outwardly away from the uniform region, and which diminish in strength with distance from the uniform region. For the purposes of the present invention, the upper fringe region may be ignored, as only the lower fringe region influences the electron beam or beams.

The pole pieces are positioned at such an angle that the magnetic field established thereby deflects the beam back downwardly and over toward the target material 13. The magnetic field between the slanted bar-shaped pole pieces is made sufficiently strong by the energizing means 16 so that the beam does not penetrate an appreciable distance into the region directly between the pole pieces, but rather is deflected through a change in direction of roughly 140° entirely or nearly entirely within the fringe region of the field and emerges from the magnetic field on the same side as the side from which it entered. Thus, the field established by the pole pieces functions in a manner similar to an optical mirror.

Referring to FIG. 2, the lines of force of the magnetic field may be seen extending between the pole pieces 14 and 15. As may also be seen, the deflection of the electrons in the electron beam takes place almost entirely within the curving or fringe portion of the magnetic field established below the region directly between the pole pieces. Because the electrons towards the outside of the curving path of the beam spend a longer period of time within the magnetic field and pass through stronger regions of the magnetic field than the electrons toward the inner edges of the curving beam, a focusing action in the plane of the curving beam path may occur. Under some circumstances, the focusing action may be so strong as to produce a sort of nodal point with subsequent diffusion of the beam. By proper adjustment of the magnetics near the electron beam gun, a sufficiently compact beam cross section may be achieved that any tendency for the beam to diffuse in the above manner is tolerable.

Due to the outwardly bowing lines of flux in the lower fringe region of the field, the divergence of the beam in the direction transverse to the plane of its curving path as it leaves the magnetic field is increased. This means that the beam deflected by the field will be defocused in the lateral direction and have a bigger impact dimension in the flow direction on the target surface that it would have if it had been projected the same distance without deflection. This is tolerable, however, if the beam cross section is kept compact by proper adjustment of gun magnetics as mentioned above. Such a compact beam may be achieved by suitable placement and energization of the pole pieces **37** at the gun **11**.

The pole pieces **14** and **15** are supported on a pair of pole piece extensions **51** and **52**, respectively. The pole piece extensions are of a ferromagnetic material and have their ends opposite the pole pieces **14** and **15** in contact with the ends of the magnetic core **53** of an energizing coil **54**. The energizing coil is energized by suitable current from the energizing means **16**.

The position and the shape of the pole pieces can be varied, depending upon the particular furnace geometry, to achieve the desired beam spot size and deflection characteristics. Condensate build-up may be easily compensated for by slight adjustment in the field strength when required. The actual distance of the pole pieces from the target and from the electron beam source is dictated by consideration of the desired impact angle of the beam and by the geometric spacing of the target and the gun. The depth of the pole pieces does not have a substantial affect on beam trajectory, since the beam does not penetrate through the region between the pole pieces. The size of the facing areas of the pole pieces, however, determines the power needed to produce the required field strength. The required field strength, of course, depends on the gun power as well as the amount of deflection desired. The angle of the poles with respect to the horizontal depends upon the angle between the incoming electron beam path and the desired outgoing beam angle. Preferably, a plane *p* including the longitudinal axes of the poles is about perpendicular to a plane which bisects the angle formed by the incoming and outgoing beam paths and which is perpendicular to a plane therethrough. A shield **60** of ferromagnetic material prevents the field adjacent the coil **54** and pole piece extensions **51** and **52** from affecting the beam.

In order to deflect the electron beam and thereby provide sweep of the beam impact spot across the surface of the molten material **13**, the directing means include a suitable set of pole pieces **61** for providing orthogonal deflection of the electron beam as it passes just above the opening **41**. Although the particular construction of the deflection means **61** is not shown and may take any suitable form, it is preferred that the deflection means **61** comprise four solenoidal type electromagnetic coils arranged with their axes intersecting and defining a rectangular planar region. The coils have cores of low magnetic reluctance which are in contact at each end to the cores of the immediately adjacent coils. Variation in the energization of the coils produces a change in the direction of the lines of force of the field established by the coils and therefore a change in the amount of deflection of the beam.

Due to the outwardly bowing lines of flux in the magnetic field produced by the pole pieces **14** and **15**, a magnification of the deflection of the beam produced by the operation of the deflection means **61** occurs on an axis perpendicular to the poles. Thus, a very wide range of sweep is available in the dimension along the hearth, as may be seen in FIG. 2. In FIG. 2, the electron beams of all the guns are indicated by dashed lines. The impact areas on the target surface are shown as small ovals or circles at the ends of the beams. By appropriate spacing of the electron beam guns and their deflecting fields, some overlap of the sweep may be achieved for a desirable redundancy in the operation of the system.

The depth at which the electron beam penetrates the region directly between the pole pieces (the region of field uniformity), is limited to that depth which would avoid undue limitation of the amount of beam sweep which is possible. Moreover, excessive penetration may result in the beam becoming to difficult to control. Accordingly, the strength of the magnetic field is selected to avoid penetration of the beam past a plane extending between the longitudinal axes of the two pole pieces.

The configuration of the pole pieces **14** and **15** may be varied so that portions thereof are slanted inwardly toward each other. This may be accomplished either by using additional dipoles **63** as shown in FIG. **3**, or by making the pole pieces themselves of appropriate configuration as shown in FIG. **4**. By the use of this type of design, a more uniform field strength may be achieved since there may be less of a tendency for field strength to fall off toward the ends of the pole pieces because of their increasing proximity.

As may be seen in FIG. **2**, a spurious field is established between the adjacent pole pieces of adjacent pairs. Thus, a spurious field is established between the pole pieces **15** and **44** and between the pole pieces **45** and **46**. Because deflection of the beam takes place almost completely in the fringe region of each main field, the fringes of the spurious fields thus established are out of the path of the electron beams, even at wide sweep angles. Thus, even though spurious fields are established between adjacent pole pieces in adjacent pairs, they produce no detrimental affect on the operation of the system.

Another advantage of the present system is that, if additional power is needed, a separate and redundant system may be placed on the opposite side of the hearth, thereby doubling the power for heating. Moreover, if desired, two electron beam guns may utilize the same pair of pole pieces for deflection, as is shown in connection with the pole pieces **46**, **47** at the far right-hand edge of FIG. **2**.

It may therefore be seen that the invention provides an improved heating system in an electron beam furnace. The invention is particularly useful in connection with a plurality of electron beams where a relatively large surface area is to be heated and where the beams are to be swept over the surface area. The invention enables the pole pieces for establishing deflecting magnetic fields to be placed closely adjacent each other without adverse affect on the operation of the system. The system is simple and reliable of operation.

Various modifications of the invention will become apparent to those skilled in the art from the foregoing description and accompanying drawings. Such modifications are intended to fall within the scope of the appendant claims.

What is claimed is:

1. In an electron beam furnace, a heating system comprising, an electron beam gun for producing an electron beam, and means for directing the beam to a target, said directing means including a pair of bar-shaped pole pieces having their longitudinal axes in a common plane and positioned to produce a transverse magnetic field in the path of the beam, said magnetic field having a region between said pole pieces of substantially straight lines of force and having a fringe region of bowed lines of force toward the direction from which the electron beam enters said magnetic field, means for varying the angle at which the electron beam is injected into the said magnetic field produced by said pole pieces to thereby vary the direction of the emerging beam, and means for energizing said pole pieces to produce a magnetic field of sufficient strength that the electron beam is deflected to emerge from the same side of said magnetic field as the side from which it enters, and is prevented from penetrating past a plane extending through the longitudinal axes of said pole pieces, said pole pieces being of a width such that substantially all of the electron beam is deflected within the fringe region of said magnetic field.

2. A system according to claim **1** wherein said energizing means are adapted to provide a field strength sufficient to cause a change in direction of the beam through an angle of between about 105° and about 165°.

3. A system according to claim 1 wherein said angle varying means produce a variation in more than one plane.

4. A system according to claim 1 wherein said pole pieces are substantially parallel with each other.

5. A system according to claim 1 wherein at least a portion of each of said pole pieces is disposed to slant inwardly toward the corresponding portion of the other of said pole pieces such that the space between said pole pieces narrows in the direction of the region directly above the target.

6. A system according to claim 1 wherein said energizing means include an electromagnetic coil having a low reluctance core, means forming a low reluctance magnetic flux path from the ends of said core to the respective pole pieces, and a magnetic shield disposed between said coil and the path of the electron beam.

7. A system according to claim 6 wherein said path forming means include a pair of upright extensions of low reluctance material forming a flux path from the ends of said core to ends of the respective pole pieces, and wherein said magnetic shield is disposed between at least a portion of said extensions and the path of the electron beam.

8. A system according to claim 1 including a further electron beam gun positioned to project an electron beam into said magnetic field on the same side thereof as the beam produced by said first named electron beam gun, said energizing means being adapted to produce a magnetic field of sufficient strength that the electron beam produced by said further electron beam gun is deflected to emerge from the same side of the magnetic field as the side from which it enters and is prevented from penetrating past a plane extending through the longitudinal axes of said pole pieces.

9. A system according to claim 1 wherein the plane common to the longitudinal axes of said pole pieces is about perpendicular to a plane which bisects the angle between the incoming and outgoing electron beam paths and which is perpendicular to a plane including such paths.

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