United States Patent

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[54] **HEATING SYSTEM FOR ELECTRON BEAM FURNACE**
5 Claims, 5 Drawing Figs.

[52] U.S. Cl. 13/31, 219/121 EB
[51] Int. Cl. H05b 5/14
[50] Field of Search 13/31; 219/121 EB, 121 R

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ABSTRACT: An electron beam furnace heating system is described comprising an electron beam gun and four solenoidal coils positioned to deflect the electron beam in a predetermined manner onto a target being heated. The solenoidal coils define a quadrangular space through which the beam passes and are energized such that oppositely disposed ones of the coils produce magnetic fields with lines of force in their cores extending in the same direction. By varying the current through the coils, the electron beam may be deflected in different directions and by different amounts to thereby control the position of impact of the electron beam on the target being heated.

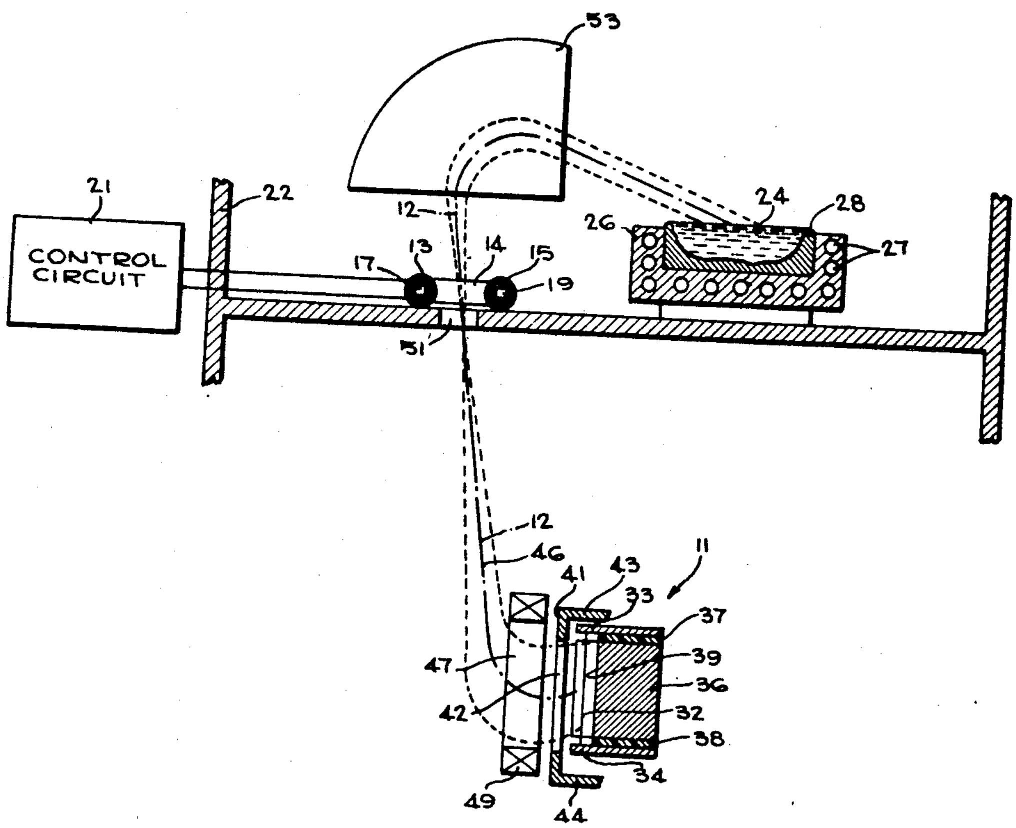
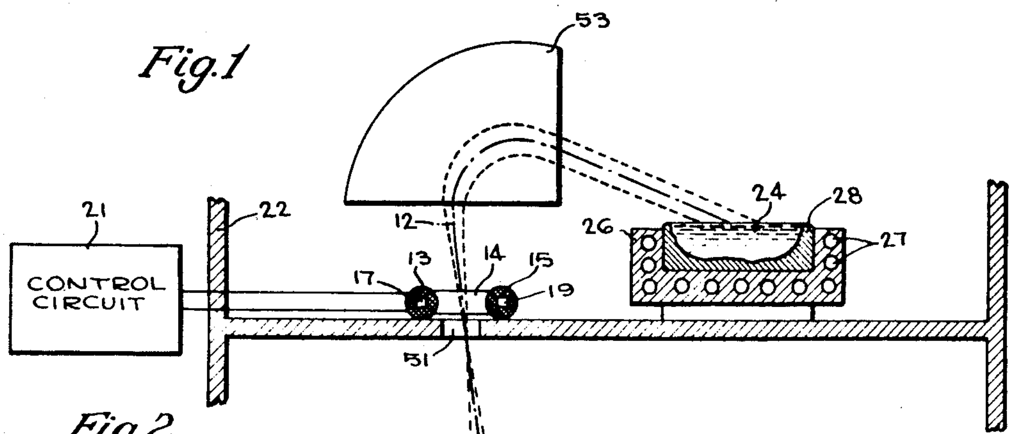


Fig.1



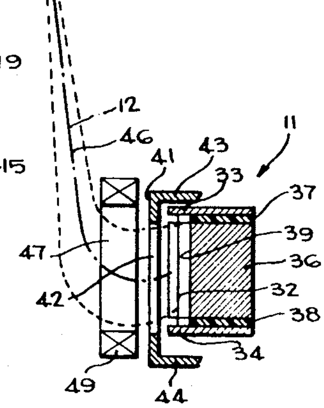


Fig.2

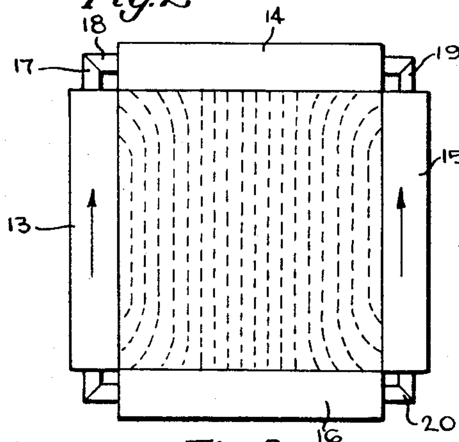


Fig.3

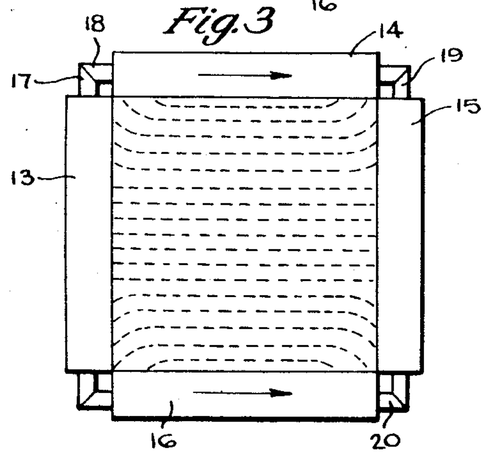


Fig.4

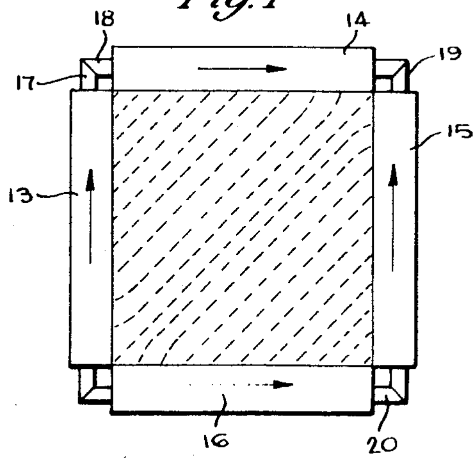
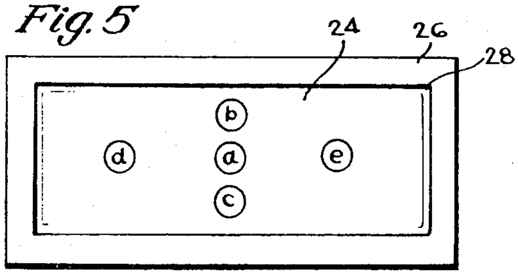


Fig.5



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HEATING SYSTEM FOR ELECTRON BEAM FURNACE

This invention relates to electron beam furnaces and, more particularly, to a heating system for use in an electron beam 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 a material. Electron beams are a particularly useful form of heating in that it is possible to inject heat into a melt locally, or to sweep a beam across a large target surface. Electron beam furnaces typically include an evacuated enclosure, a heating system comprising one or more electron beam guns with associated deflection systems for directing and focusing the beams, and a target such as a container for molten material being processed, or a substrate to be heated prior to or during coating.

Depending upon the particular type of processing being carried out, a container for 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 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 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 metal 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 container which may be utilized 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 deflecting the electron beam through a curving path of 180° or more, contamination and shorting of the electron beam gun is minimized.

In some types of electron beam furnaces, large target surfaces are to be heated. For example, where molten material is being processed on a large hearth, or where strip material being coated is being preheated by electron beams, a very large target surface area is presented for heating. In such cases, it is often desirable to sweep the beam in two or more directions in order to minimize the number of electron beam guns required while still achieving a uniform thermal pattern on the target surface. In order to achieve the desired electron beam sweeping while deflecting the beam through more than 180°, transverse magnetic fields which are variable in strength have been utilized. One desirable way of producing an orthogonal or x and y axis sweep pattern is to utilize at least two transverse fields having their flux lines oriented 90° with respect to each other and the electron beam path. 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 the two transverse magnetic fields closely adjacent each other may be extremely difficult due to mutual interference and distortion of the fields. For the same reason, the heating of large surface areas in electron beam furnaces by employing a large number of electron beam guns with separate deflecting fields for each of the beams is also difficult.

Typically, a magnetic field established between pole pieces has a portion of generally uniform strength near its center, and exhibits considerable variation toward its edges. For maximum conservation of space and good control over the beam position, it is desirable to maximize the size of the uniform portion of the field for a given pole piece spacing. This is because nonuniform portions of a field make beam control difficult, and sometimes require compensation by appropriately varying the overall strength of the magnetic field. Previously known systems have experienced some difficulty in achieving fields with large uniform portions unless the entire field was made large by using large pole pieces and wide spacing therebetween. Not only does this require more furnace space, but larger pole pieces and pole piece spacing require correspondingly greater power for a given field strength.

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

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

Another object of the invention is to provide an electron beam furnace heating system in which orthogonal control over the deflection of electron beams is provided by means of transverse magnetic fields, and in which volume requirements are minimized.

Another object of the invention is to provide an electron beam furnace heating system in which orthogonal control over the deflection of an electron beam of relatively large cross section is provided by means utilizing a minimum of space.

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 view of part of an electron beam furnace incorporating a heating system in accordance with the invention;

FIG. 2 is a plan view of a portion of the apparatus of FIG. 1 illustrating one of the magnetic fields produced thereby;

FIG. 3 is a view similar to FIG. 2 illustrating another magnetic field produced thereby;

FIG. 4 is another view similar to FIG. 2 illustrating still another magnetic field produced thereby; and

FIG. 5 is a plan view illustrating the result of a particular way of operating the apparatus of the invention.

Very generally, the electron beam furnace heating system of the invention comprises an electron beam gun 11 for producing an electron beam 12. Four solenoidal coils 13, 14, 15 and 16 are arranged with their axes forming a rectangle. The coils are positioned so that the path of the electron beam passes through the region defined by the coils. Each of the coils has a core 17, 18, 19 and 20, respectively, of low-magnetic reluctance material. Means 21 are provided for supplying an energizing current to the coils such that oppositely disposed ones of the coils produce magnetic fields with lines of force in their cores extending in the same direction. The energizing means include means for varying the current to the coils in a predetermined manner.

Referring now to FIG. 1, one embodiment of the invention is illustrated. The electron beam furnace includes an evacuated enclosure 22, only part of which is shown. A molten material target 24 is contained in an elongated container 26 which is cooled by circulating coolant in passages 27 to form a layer or skull 28 of solidified molten material between the molten material and the container walls. The container 26 is illustrated as a hearth into which molten metal flows from a launder, not shown, at one end. The contents of the hearth flow along the direction perpendicular to the paper of the drawing and are discharged at the opposite end from which they are supplied through suitable means, not shown. The level of the molten metal 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 iron 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 thermal gradients to produce convection currents at the surface for greater exposure of the material to the vacuum.

A plurality of electron beams are utilized to maintain heating of the target molten material **24** in the hearth **26**. The electron beams may be produced with a plurality of electron beam guns **11** similar in structure and design, each having its own deflection system as described below in connection with the gun **11**.

The electron beam gun **11** 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 electron beam gun **11** includes an elongated emitter **32** for producing electrons. The emitter is preferably a tungsten wire and extends between the supporting members **33** and **34**. Means, not illustrated, provide a direct current potential across the members **33** and **34**, resulting in a flow of direct current through the emitter **32**. The current flow raises the temperature of the emitter causing it to produce free electrons.

The free electrons produced by the emitter **32** are reflected on three sides by a shaping electrode **36**. The electrode **36** is insulated from the emitter support members **33** and **34** by insulating strips **37** and **38**, respectively. The shaping electrode **36** is formed with an elongated recess **39** through which the emitter **32** extends. When the shaping electrode is maintained at the emitter potential, by suitable connection not illustrated, the electrons produced by the emitter **32** tend to move out of the open end of the recess **39** and away from the shaping electrode **36**.

The electrons leaving the recess **39** in the shaping electrode **36** are accelerated into a beam by an accelerating electrode **41** and pass through an opening **42** therein. The accelerating electrode **41** consists of a plate with two right angle extensions **43** and **44** thereon which are attached to suitable mounting means, not illustrated. The plate **41** is maintained at a potential which is substantially more positive than the potential of the emitter and 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 **32** at an acute angle in the major axis plane. The axis of the beam is indicated by the dash-dot line **46**, which represents the center of the ribbon beam. The nonnormal orientation of the initial electron path with respect to the emitter **32** is caused by the high intensity circumferential field produced by DC heating current passing through the emitter.

After leaving the anode opening **42**, the electron beam 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 **47**, only one of which is illustrated. The pole pieces extend generally parallel with the emitter **32** and each other and are positioned on either side of the beam **46** parallel with its major axis plane. A magnet **48** extends between the upper ends of the pole pieces **47**, and a magnet **49** extends between the lower ends of the pole pieces **47**. 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 out of the plane of the paper as illustrated in the drawing, thereby causing an upward deflection of the electron beam **46** as illustrated. The effect of the field on the electron beam also produces a convergence of the opposite edges of the beam toward each other in the plane of the curving path due to a longer path length of the electrons toward the lower edge of the beam in the magnetic field established by the pole pieces **47**. The details of the deflecting and focusing of the beam are set out more fully in the aforesaid patent.

A generally horizontal vapor barrier **52** is provided above the electron beam gun **11**. The vapor barrier is provided with an opening **51** therein through which the electron beam passes upwardly into the remaining portion of the evacuated furnace chamber. By separating the region in which the electron beam gun **11** is disposed from the region in which the actual heating of the target takes place, the electron beam gun is exposed to a lesser amount of vapor particles, particularly if a separate pumping system is provided for the portion of the furnace in which the electron beam gun is disposed.

A pair of wedge-shaped pole pieces, only one of which is shown at **53**, are disposed in the furnace above and to one side of the target material **24**. Suitable electromagnetic energizing coils, not shown, are provided for the pole pieces to produce a strong transverse magnetic field extending therebetween. As the beam passes through this field, it is deflected through an angle of about 150° to impinge upon the surface of the molten material **24**. Since the electrons toward the outer edge of the curving beam remain in the field longer than the electrons toward the inner edge, some convergence of the beam results, effecting a desired focusing effect to produce a dense spot for heating the material **24**. Other suitable means that the pole pieces **53** may be used to deflect the beam onto the target, within the scope of the present invention.

As previously mentioned, it is desirable that the beam spot on the surface of the target **24** be swept in a desired pattern to achieve the thermal heating pattern desired for maximum beneficial operation of the system. Except in a region of inversion or flip over, such as at the opening **51** in the barrier **52**, an electron beam produced by an elongated emitter is typically of relatively large cross section. Accordingly, deflection of such beam in an orthogonal manner may be difficult for the reasons previously discussed, In accordance with the invention, controlled orthogonal deflection is provided by four solenoidal type deflection coils **13**, **14**, **15** and **16**. The solenoids or coils are arranged in a quadrangle to define a quadrangular space. In the illustrated apparatus, the coils define a rectangle and their cores **17**, **18**, **19** and **20** are in contact at their ends, forming a low reluctance rectangular loop. The coils on opposing legs or opposite sides of the rectangle are electrically connected in parallel or series and the polarity is such that they generate a magnetic field in the same direction, e.g., in the direction of the arrows. In other words, the direction of the lines of force in the coil cores **17** and **19** are toward the same end of the quadrangle, and the directions of the lines of force in the coil cores **18** and **20** are also toward the same end of the quadrangle.

Each of the coils **13**, **14**, **15** and **16** is comprised of one or more helical windings on its ferromagnetic core and may be of a construction similar to those types of coils utilized in solenoids. Preferably, the length of each of the coils is at least twice its diameter. The coils are energized by passing direct current therethrough from the control circuit **21**. A high degree of uniform field intensity results from the fact that the leakage flux of the individual wires of the respective coils reinforces the lines of the main field in the region along the edges of the coils, where field strength might be expected to diminish in a more conventional arrangement. As is known in the art, leakage flux is produced by the current passing through each turn. In a long coil, the leakage flux from each turn merges into that of the adjacent turns, forming long lines of flux running along the coil adjacent its outer surface and parallel with the coil axis. The use of a pair of solenoidal coils on each side of the rectangular space energized in the manner described above causes the main field to be reinforced at its edges by the leakage flux of the coils. This produces a field in which the strength can be maintained uniform to about plus or minus 10 percent. The system can be placed in quite close proximity to the adjacent magnetic structures without detrimental effect.

Referring to FIG. 2, with the coils **13** and **15** energized in the above described manner, and with the coils **14** and **16** not energized, the lines of force are illustrated as extending for the most part generally parallel to the axes of the energized coils. The path for these force or flux lines is through the respective cores **17** and **19** of the coils and is in the same direction in each of the cores. The magnetic path is then through the cores of the unenergized coils part way and then across the quadrangular space.

Similarly, with the coils **14** and **16** energized, and the coils **13** and **15** not energized, the result is shown in FIG. 3. Here it can be seen that the flux lines in the rectangular region defined by the coils extend perpendicularly to the direction of the flux lines of FIG. 2, that is, they extend parallel with the axes of the energized coils. Similar to the situation illustrated in FIG. 2, the path for the flux lines is through the cores **18** and **20** and is in the same direction in each of the cores, and through part of the cores of the unenergized coils.

Referring now to FIG. 4, the results of equal excitation of both pairs of solenoidal coils are illustrated. Here it can be seen that, with a square arrangement of coils, the flux lines extend at a generally 45° angle with the flux lines produced when only one pair of coils is energized. When the excitation of the respective coil pairs is varied relative to each other, either in direction or amplitude or both, the direction of the flux lines varies accordingly. Thus, any desired angle of flux lines may be achieved depending upon the relative excitation of the coil pairs and, of course, the overall strength of the magnetic field may also be varied by varying the degree of excitation.

The illustrated embodiment employs solenoidal coils and cores of equal length, thereby defining a square magnetic field. In some circumstance, furnace geometry or the particular characteristics of the system may render a rectangular or other form of quadrangular magnetic field more preferable. For example, a wider sweep range may be desired in one direction and may be achieved by an appropriate lengthening of the coils which extend in that direction. In any case, the resultant field is highly uniform and therefore extremely advantageous in deflecting electron beams of relatively large cross section. Moreover, for a given beam sweep distance, the required overall size of the magnetic field is minimized when the beam is produced in accordance with the invention.

Referring to FIG. 5, the results of various levels of energization of respective coils may be seen in terms of the effect on deflection of the beam. Spot position "a" represents the beam position when no energizing current is supplied to any of the coils **13–16**. This position is achieved by appropriate geometry in the system and may be designated as the reference position.

Position "b" represents the case in which current is passed through the coils **13** and **15** but not through coils **14** and **16**, and wherein the current is passed in a direction to cause the appropriate action of magnetic forces on the electrons of the beam to move the beam in that direction. The current may be either positive or negative negative upon the direction in which the coils are wound. A current of opposite polarity and approximately the same magnitude will cause the beam to be deflected to the position "c".

Similarly, lateral deflection is achieved by appropriate energization of the coils **14** and **16**. The position "d" represents maximum deflection with current of one polarity in the coils **14** and **16** and no current in the coils **13** and **15**. The position "e" represents maximum deflection due to current in the opposite direction from the former case. Positions along depending line between the spots "a", "b" and "c" may be achieved by appropriate variation of the strength and direction of the current in the coils **13** and **15**. Similarly, variation in the position of the beam along a line between the spots "a", "d" and "e" may be achieved by appropriate variation of the current in the coils **14** and **16**.

In order to direct the beam to the other positions not on a direct line between either "b" and "c" or "d" and "e", the relative energization and overall energization of the various coils is suitably adjusted. In actual practice, the two magnetic circuits appear to operate independently and thus orthogonal positioning of the beam spot may be achieved by considering the current through the coils **13** and **15** as the y coordinate and the current through the coils **14** and **16** as the x coordinate. Thus very precise spot positioning is achievable by this simplification, even though the operation of the magnetic field itself is somewhat more complex.

In operation, the system of the invention is substantially unaffected by the close proximity of ferromagnetic structural elements or even by other magnetic fields. Thus, less space is required for the system. In addition, a further space saving results from the fact that orthogonal deflection is achieved by a deflection arrangement that occupies very little distance along the beam path.

It may therefore be seen that the invention provides an improved heating system for use in an electron beam furnace system. Beam sweep is achievable by means of apparatus which occupies a minimum amount of space and highly precise adjustment of beam position is possible. Construction of the system is simple and low in cost, and due to its simplicity the system is highly reliable in operation. The system may be used to control a beam which is directed in a substantially linear path from the gun to the target, or may be used along with other deflecting means as in the illustrated embodiment.

Various modifications of the invention in addition to those shown and described herein 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, four solenoidal coils arranged with their axes forming a quadrangle, said coils being positioned so that the path of the electron beam passes through the region defined by said coils, each of said coils having a core of low magnetic reluctance material, and means for providing an energizing current to said coils such that oppositely disposed ones of said coils produce magnetic fields with lines of force in their cores extending in the same direction, said energizing means including means for varying the current to said coils in a predetermined manner.

2. A heating system according to claim **1** wherein the cores of said coils are in contact with each other at their ends to form a quadrangular low reluctance loop.

3. A heating system according to claim **1** wherein said current varying means are capable of varying the current in both direction and magnitude through the respective pairs of opposite coils independently.

4. A heating system according to claim **1** wherein the electron beam path is substantially perpendicular to a plane containing the axes of said coils.

5. A heating system according to claim **1** wherein the coils are arranged with their axes forming a rectangle.

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