

Feb. 15, 1966

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3,235,647

ELECTRON BOMBARDMENT HEATING WITH ADJUSTABLE IMPACT PATTERN

Filed June 6, 1963

3 Sheets-Sheet 1

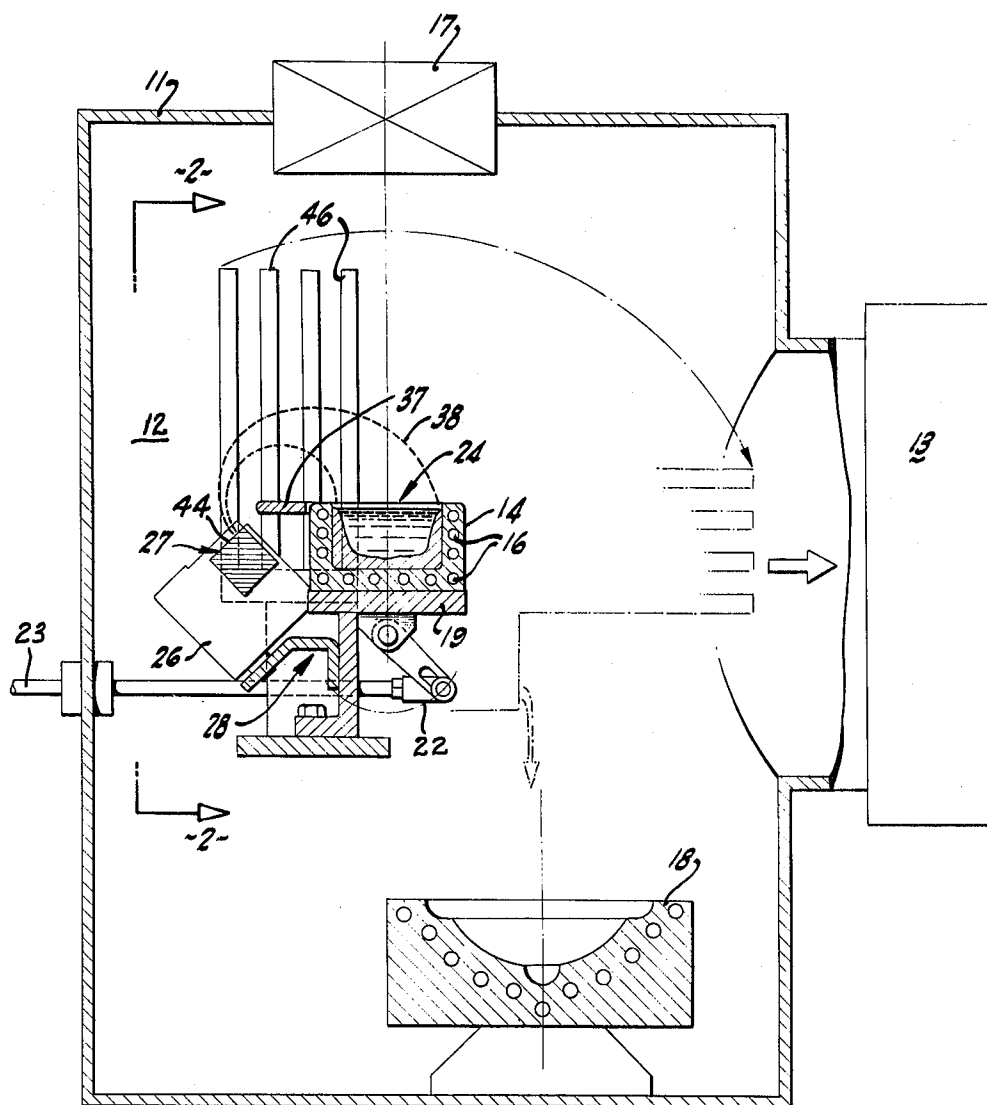


FIG-1

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3 Sheets-Sheet 2

FIG-2

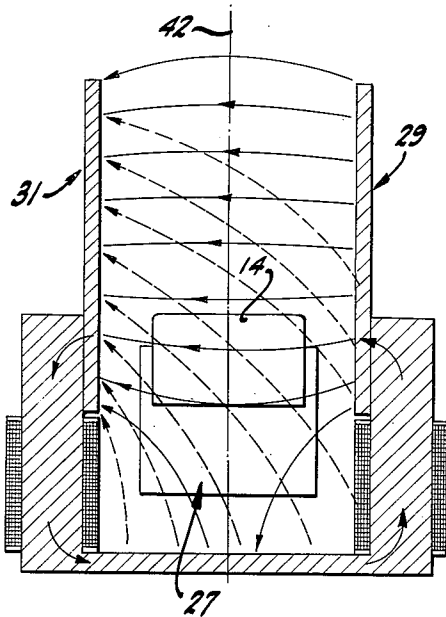
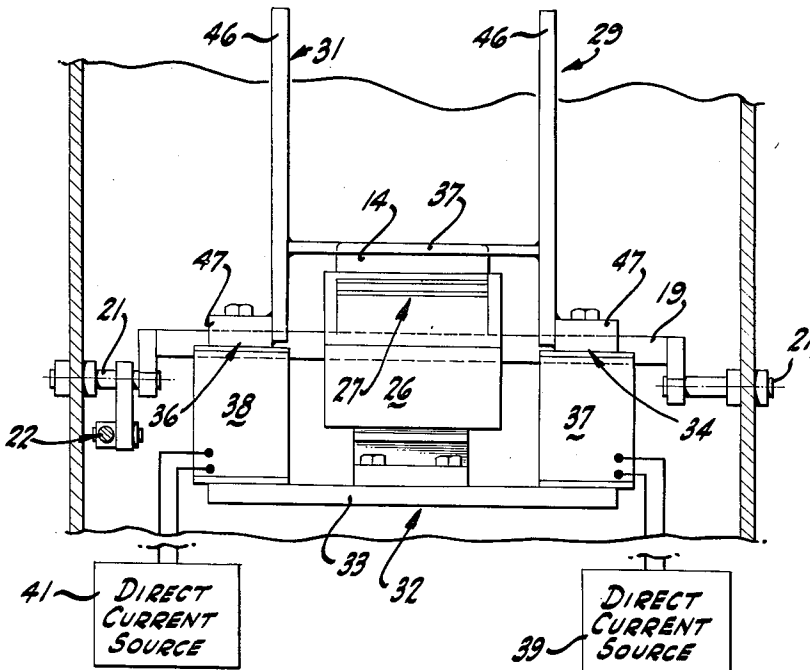
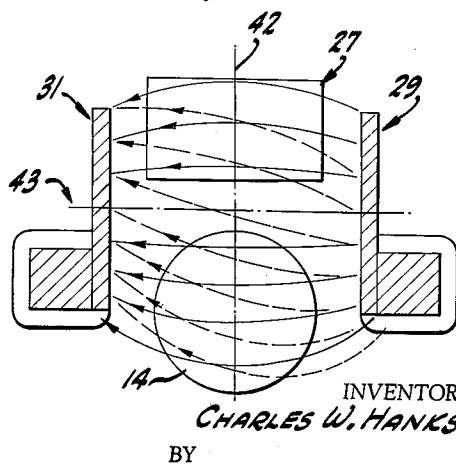


FIG-3

FIG-4



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3 Sheets-Sheet 3

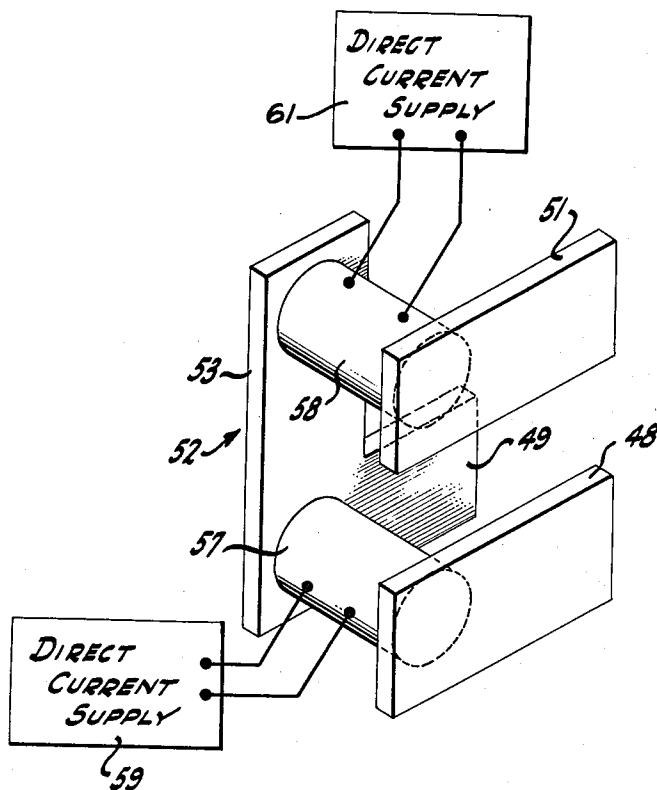


FIG-5

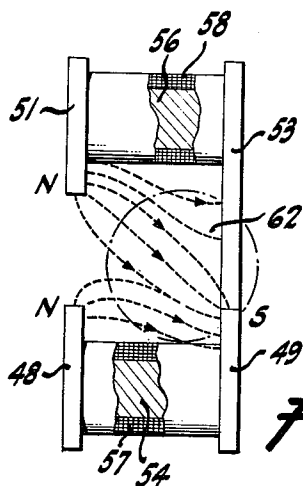


FIG-6

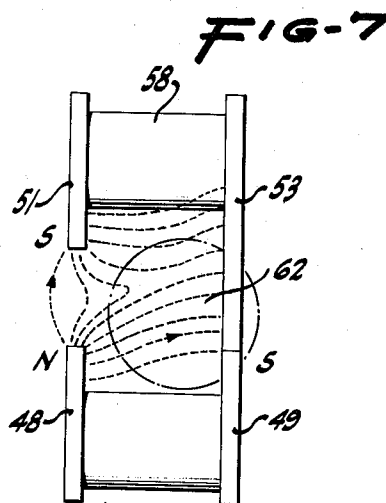


FIG-7

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3,235,647

ELECTRON BOMBARDMENT HEATING WITH ADJUSTABLE IMPACT PATTERN

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7 Claims. (Cl. 13-31)

The present invention relates generally to electron bombardment heating as variously employed in high-vacuum furnaces to treat material in the conduct of casting operations, vapor coating processes, metal purification processes, and the like. The invention is more particularly directed to an improvement in the magnetic guidance of electron beams to facilitate substantial variation in the pattern of bombarding electrons at impact with the material to be heated.

Electron bombardment heating is extensively employed in high-vacuum furnaces as a mechanism for treating material undergoing various processes therein. More particularly, these high-vacuum furnaces typically include an enclosure which is continuously evacuated to a high vacuum. Material melted within the enclosure becomes highly purified inasmuch as any volatile impurities, occluded gases, and the like evolved from the material during the melting thereof is withdrawn by the continuous evacuation of the enclosure. The melted material is in some instances streamed into a cold mold wherein the material is further heated at the open top of the mold to maintain a molten pool of material within the mold atop a solidifying ingot therein. The ingot is of highly-purified material and may be continuously withdrawn from the lower portion of the mold. In other instances, the material may be melted and maintained molten within a crucible and subsequently cast therefrom into a mold disposed within the vacuum enclosure to form a casting of highly-purified material. In still other instances, vapors evolved from the molten material within a crucible are deposited upon a surface as a plated layer or coating of the material in highly-purified form. Irrespective of the specific arrangement of components within the vacuum enclosure, or the specific processes conducted therein, heating of the material to melt same and/or maintain same molten in the high-vacuum surroundings is most effectively accomplished by bombardment of the material with electrons. In this regard, the bombarding electrons are generated by one or more electron guns, each including an electron-emissive cathode and accelerating anode structure for directing the electrons evolved from the cathode upon the crucible, mold, or other desired target, as an electron beam. The electron velocity, and therefore energy, of the beam may be readily controlled commensurate with a desired extent of heating of the material at the particular target.

In conjunction with the foregoing employment of electron guns magnetic guidance is advantageously utilized to focus the beam upon the target and to control the impact pattern of the electrons thereon. In this regard, an electron gun is typically disposed at a remote location relative to the crucible, or other target, and a magnetic field is generated in space with regions of the field disposed adjacent the gun and target. The magnetic lines of force may be established generally parallel to the target surface, and electrons are directed from the gun into the magnetic field transversely to the lines of force. The magnetic field deflects the electrons along curved trajectories to the target with the pattern of impact of the electrons thereon being determined by the characteristics of the magnetic field. It will, of course, be appreciated that impact pattern requirements may vary considerably depending upon the nature of the particular target to be

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bombarded, as well as other conditions prevailing within the high-vacuum enclosure. For example, where the target is material within the open top of a cylindrical crucible and a single gun is employed to generate the electrons for bombarding same, the magnetic field characteristics should be such as to deflect the electrons into a substantially circular impact pattern which uniformly covers the top of the crucible without substantial spill-over of the beam. In another arrangement, three electron guns might, for example, be employed in the bombardment of a circular target, such as the open top of a cylindrical crucible. These guns may be arrayed with separate magnetic guidance systems to direct electron beams on the target from positions angularly displaced 120 degrees apart. Thus, for the most efficient utilization of the beams in the coverage of the target area, the impact pattern of each beam is a 120-degree sector of the circular target area, or triangle having an apex angle of 120 degrees. With these circular sectors or triangles circumferentially adjacent each other at the target surface area, it will be appreciated that efficient overall coverage thereof is obtained. Heretofore, in order to obtain a beam impact pattern having a given desired configuration such as those just mentioned, it has been necessary to tailor the magnetic guidance field to suit the particular situation. This has been rather tediously accomplished through shaping of the magnetic field by empirical shimming of the magnet pole pieces generating same, until a magnetic field configuration is provided which is observed to produce the desired impact pattern at the target. Thus, aside from the difficulties encountered in tailoring the field in the foregoing manner, the resulting field configuration is substantially fixed and is unsuited to the production of any but the particular impact pattern for which it was specifically designed.

The present invention overcomes the foregoing disadvantages and limitations associated with previous methods of adjusting electron beam impact pattern by the provision of a method and means for generating magnetic guidance field whose characteristics are variable in such a manner that electrons may be thereby focused into substantially any desired impact pattern at a target. More particularly, the present invention provides for the generation of a magnetic guidance field by a plurality of pole pieces, or the like, which are magnetically coupled by a low-reluctance flux path interconnecting same. Provision is made for the controlled variation of flux densities in respective linking portions of the flux path between the various pole pieces to, in turn, facilitate separate adjustment of the densities of the lines of force adjacent the respective pole pieces. Separate coils magnetically linked with the linking portions of the flux path and means for separately controlling current flow through these coils may be, for example, employed to vary the flux densities in the respective linking portions. Through appropriate control of the relative proportions of flux density existing in the respective linking portions of the flux path, the lines of force extending between the pole pieces may be readily adjusted to have varied amounts of skewness or slant. The extent and direction of skewness of the magnetic lines of force determine the positions at which electrons directed into the field impact a target. Consequently, by varying the skewness, the points of electron impact at the target and thus the impact pattern is varied. A wide variety of impact pattern configurations are readily attainable through control of the magnetic field in the foregoing manner. Moreover, continuous movement of the impact pattern over the target is herein effected by shifting maximum flux density alternately between linking portions of the flux path to thus alternate the direction of skewness of the magnetic lines of force. A relatively large target area may be covered by sweeping the im-

pect pattern in this manner, provided of course that some nonuniformity in heating of the target surface with respect to time can be advantageously employed or at least tolerated. Sweeping of the impact pattern over the target surface in the foregoing manner may additionally be employed to facilitate thermal stirring of a pool of molten material in a crucible or the like, where same comprises the bombardment target area. Further to the foregoing, in a preferred embodiment of the apparatus of the invention, provision is made to facilitate minimized obstruction to the evacuation of the volume between the pole pieces employed in the generation of the magnetic guidance field for the ready adjustment of beam impact pattern upon a target. Accordingly, gaseous material normally existing between the pole pieces of a magnetic guidance system employed in a high-vacuum furnace are evacuated to a greater extent than heretofore possible in conventional arrangements and as a result improved control over impact pattern is provided since disturbance of electron trajectories by collision with gaseous materials is minimized.

The invention may be better understood from the following more detailed description thereof in conjunction with the accompanying drawings, in which:

FIGURE 1 is a vertical section through an electron beam vacuum furnace embodying improved electron beam magnetic guidance apparatus in accordance with the present invention,

FIGURE 2 is a fragmentary sectional view taken at line 2—2 of FIGURE 1,

FIGURE 3 is a schematic illustration of improved magnetic guidance apparatus in accordance with the invention depicting magnetic lines of force thereby generated, as viewed in rear elevation,

FIGURE 4 is a schematic illustration of the guidance apparatus depicting magnetic lines of force produced thereby as viewed in plan,

FIGURE 5 is a perspective view, partially in schematic of an alternative form of magnetic guidance apparatus in accordance with the invention,

FIGURE 6 is a schematic illustration of the apparatus of FIGURE 5, as viewed in end elevation, depicting magnetic lines of force skewed in accordance with the method of the invention, and

FIGURE 7 is a view similar to FIGURE 6, but depicting magnetic lines of force skewed in the opposite direction in accordance with the method.

Considering first one type of electron beam high-vacuum furnace in general, and referring to FIGURE 1, there will be seen to be illustrated an enclosure 11 defining a chamber 12 communicated with evacuation means 13 for continuously pumping the chamber in order to maintain a high vacuum therein. Within the vacuum chamber 12 there is disposed a container into which material such as metal may be deposited. In the particular embodiment herein described, such container is provided as a crucible 14 formed of copper, or the like, with passages 16 therein for circulation of a coolant to maintain the walls of the crucible at a nondestructive relatively low temperature compared to that of material within the crucible heated to a molten condition. In the illustrated embodiment, the crucible 14 is movable between an upright position wherein material to be heated may be introduced to the open top of the crucible through a seal lock 17 or the like provided in the top of enclosure 11 in overlying relation to the crucible, and a downwardly-pivoted pouring position wherein molten material in the crucible is cast into a mold 18 or the like appropriately positioned at the base of the enclosure. Controlled tilting of the crucible is facilitated in a manner analogous to that disclosed in a copending application for U.S. Letters Patent of Hugh R. Smith, Jr., Serial No. 221,807, assigned to the same assignee as the present application, the crucible being mounted upon a platform 19 with stub shafts 21 journaled in the walls of enclosure 11 with at least one

crank 22 employed in association with one of the shafts 21 and coupled to a remotely-controllable pushbar linkage 23. Through controlled actuation of a pneumatically-operated piston, or the like (not shown), coupled to the linkage 23, same may be retracted or extended to thereby pivot the crucible between its upright material receiving, and tilted pouring positions. It should be noted that the particular illustration of the crucible 14 herein as being tiltable and employed in relation to the mold 18 to cast molten material therein is purely exemplary and that the crucible may as well be fixed and employed for other purposes, such as in the vapor deposition of molten material contained therein upon an appropriately disposed overlying surface. Further to the foregoing, the container for material referred to hereinbefore, in its broad connotation is to be taken as including, in addition to crucibles, cold molds of a type into which molten material is continuously streamed from solid melt stock undergoing heating and melting within the chamber 12, with the material solidifying in the lower portions of the cold mold and supporting a molten pool at the upper end thereof whereby the solidified portion may be continuously withdrawn from the mold in the form of an ingot of highly-purified material.

Heating of material within the vacuum chamber 12 to initially melt same, and maintain same molten in various phases of any desired process being conducted therein, is advantageously accomplished by electron bombardment heating. In this regard, one or more electron guns are provided to direct electron beams upon the material being processed at the various process stations thereof. Where the process involves the holding of the material within a crucible, one or more electron guns are provided to direct electron beams into the open top of the crucible to initially melt and/or maintain the material therein molten. Similarly, material within molds or other containers are frequently maintained molten by electron bombardment heating, while in other instances bombarding electron beams are directed upon the material as introduced to the chamber in the form of solid melt stock, to initially melt same and effect continuous streaming thereof into a cold mold or other container. Irrespective of the form or particular disposition of the material at a process station whereat the material is subjected to heating by electron bombardment, the term "target" is herein employed to designate the surface of the material upon which the electrons are directed. In the particular embodiment of a furnace as illustrated in the drawings and herein described, the target is the exposed surface, as generally indicated at 24, of material held within the open-topped cylindrical crucible 14. In the present instance, electrons are directed upon the surface 24 from a single electron gun 26 which, for example, may be structurally provided and operated as disclosed in my prior application for U.S. Letters Patent, Serial No. 37,615, filed June 21, 1961, now Patent No. 3,177,535. The gun is advantageously, although not necessarily, disposed forwardly of the crucible and downwardly from the open top thereof. As is well-known, with such disposition of the gun 26, contamination of the electrode structure 27 thereof by deposition of vapors rising from the molten material within the crucible is greatly minimized. In addition, the gun 26 in the instant embodiment is provided integrally with the crucible 14, such gun being mounted upon bracket structure 28 carried by the crucible. Thus, the gun and crucible are tiltable as a unit in a manner analogous to that provided by the tiltable crucible arrangement of the hereinbefore-referenced copending patent application Serial No. 221,807.

It will be appreciated that in order for electrons generated from the electrode structure 27 of the gun 26 to bombard the target surface 24 of material within the crucible 14, means must be provided to guide the electrons along curved trajectories extending between the gun and target surface. To this end, means are provided to gen-

erate a magnetic field having lines of force extending over the open top of the crucible and adjacent the electrode structure 27 of the gun, transverse to the directions of movement of electrons emitted therefrom. Preferably, this magnetic field generating means includes a pair of parallel-spaced pole pieces 29, 31, respectively disposed on opposite sides of the crucible 14. These pole pieces are advantageously of substantially flat vertically elongated rectangular configuration having their upper ends extending above the open top of the crucible and their vertical side edges respectively adjacent an intermediate region of the crucible and a location forwardly of the electrode structure 27 of the gun 26. Thus, a forward portion of the crucible and the electrode structure of the electron gun are disposed within a spatial region transversely defined between the pole pieces 29, 31. In addition, means are provided to connect the lower ends of the pole pieces through a low-reluctance flux path, and preferably such means comprises a substantially U-shaped yoke 32 of high-permeability material such as soft iron. Such yoke includes a transverse web portion 33 extending between the lower ends of upright parallel leg portions 34, 36 respectively secured in magnetically-coupled relation to the base edges of pole pieces 29, 31. The entire pole piece and yoke assembly is secured to the crucible 14, as by means of a bracket 37 extending transversely between the pole pieces and peripherally secured to the forward portion of the crucible 14. The yoke 32 links magnetic winding means for inducing magnetic flux within the yoke. A closed magnetic circuit is of course defined by the yoke and pole pieces and the air space extending transversely between the latter. As a result, lines of magnetic force extend substantially transversely between the pole pieces and are distributed in a spatial region laterally and upwardly adjacent the electrode structure 27 of gun 26 and the forward portion of the crucible 14. In plan view, the lines of force adjacent the vertical side edges of the pole pieces are of generally convex configuration projecting outwardly from the pole piece edges. These convex lines of force constitute fringe regions of the magnetic field disposed at longitudinally opposite ends of a substantially uniform central field region wherein the lines of force are generally linear and more closely spaced. The magnetic field strength in the region of the fringing fields is less than that in the central region of the field and the electrode structure 27 of the electron gun is disposed in one fringing field, whereas the target surface 24 at the top of the crucible is disposed in the other fringing field. Thus, electrons emitted from the electrode structure 27 enter a fringing field transversely to the lines of force and are deflected along curved trajectories extending through the central field region of relatively high field strength and then through the other fringing field into the top of the crucible 14. Through appropriate adjustment of the strength of the field established between the pole pieces, the electrons are focused to form an impact pattern at the target surface 24 substantially covering same as indicated by envelope 38 of the focused electron beam. It has been found, however, the impact pattern at the target surface 24 is not circular to conform to the configuration of the target surface commensurate with optimum efficiency of beam utilization. Instead, the impact pattern includes opposed drawn-in portions such that the impact pattern configuration substantially resembles that of a keyhole. Thus, in order to obtain complete coverage of the target surface 24, the beam impact pattern must be sufficiently enlarged that the minor dimension thereof between the opposed drawn-in portions is as great as the diameter of the circular target area. As a result, there is substantial spillover of the beam beyond the target area along the major axis of the keyhole pattern. These electrons beyond the target area of course serve no useful purpose and detract from the efficiency with which the beam is utilized to bombardment heat the target area. As noted previously herein, attempts have been made to increase the efficiency

of beam utilization through appropriate shaping of the magnetic guidance field in such a manner as to vary the impact pattern to the end of eliminating the drawn-in regions thereof whereby the pattern more closely resembles a circle. Previous attempts to obtain a substantially circular impact pattern by shaping of the guidance field have entailed the rather tedious procedure of empirically shimming the pole pieces until the desired pattern is observed at the target. Similarly, empirical shimming of the pole pieces has been employed to provide desired impact pattern configurations other than circular for various other applications. Aside from the foregoing disadvantages arising from the tedious nature of the field-shaping procedure, it is to be noted that the field, once shaped to provide a given impact pattern, is not readily susceptible to reshaping to provide a different impact pattern. Consequently, little or no control has been available in past field-shaping methods employed in association with the magnetic guidance of electrons for bombardment heating purposes in high-vacuum furnaces.

In accordance with the present invention, provision is made to facilitate shaping of magnetic guidance fields in a relatively simple, readily controllable manner to provide adjustment of the impact pattern of a bombarding beam of electrons to conform to a variety of target configurations, and/or to suit a variety of bombardment heating applications commensurate with optimum efficiency of beam utilization. For example, the method hereof may be employed in the foregoing situation to control the field between pole pieces 29, 31 in such a manner as to produce a circular impact pattern conforming to the top of crucible 14. In general, a variable impact guidance method is employed, which may be applied in various ways in a high-vacuum furnace to facilitate bombardment heating of material therein with the foregoing advantages irrespective of the particular form of the material and the specific stage of processing which it undergoes. For example, the material may be in the form of a solid ingot of melt stock continuously introduced to the furnace for subjection to heating at its leading end, to melt the material and stream same into a cold mold, crucible or the like. Alternatively, the material may be molten and contained within a crucible, cold mold or the like. The method of the invention applies equally as well in any case. More explicitly, in accordance with the method of this invention, a magnetic guidance field is generated in the vicinity of a target represented by material to be treated in whatever form (i.e. solid melt stock, molten material held within a container or the like) as disposed within the high-vacuum region of a vacuum furnace. In the generation of the field, there is established a low-reluctance flux path interconnecting a plurality of pole pieces adjacent the target. Magnetic flux is then induced in the flux path to establish the magnetic field, lines of force of the field extending between the pole pieces and hence occupying a region of space adjacent the target. The electrons are then directed into the field transverse to the flux lines thereof between the pole pieces for focusing upon the material representing the target. Finally, the flux densities in portions of the flux path linking respective ones of the pole pieces are controllably, separately varied to skew or slant the directions of the lines of force extending between the pole pieces. It has been found that through such controlled variation of the degree and direction of skewness of the field lines, substantially any desired impact pattern at the target of electrons directed transversely into the field may be produced.

With regard to the particularly salient step of the method of controllably, separately varying the flux densities in linking portions of the flux path between the respective pole pieces, it will be appreciated that same may be most readily accomplished through electromagnetic induction. More particularly, this step of the method preferably consists in separately and controllably induc-

ing flux in the respective linking portions of the flux path in controlled proportions commensurate with the observation of an impact pattern having a desired configuration. The foregoing may be accomplished by means subsequently described in detail herein. Moreover, this step of the method may be somewhat modified if desired to provide a swept impact pattern. In this regard, magnetic flux may be induced alternately in respective ones of the linking portions of the flux path or the flux may be alternately reversed in direction in one linking portion to thereby alternately skew the lines of force of the magnetic field in opposite directions and accordingly effect continuous movement and variation in the configuration of the impact pattern of the electrons upon the target. As a result, thermal agitation or stirring of the material representing the target being bombarded is produced, which effect is sometimes highly desirable.

The method of the invention likewise applies in situations where a target is bombarded by electrons from a plurality of distinctly separate focused directions, as opposed to a single direction. In this regard, a plurality of low-reluctance flux paths, each interconnecting a plurality of pole pieces, are established at equally circumferentially-spaced radii emanating from a point on the target. Magnetic flux is separately and controllably induced in respective linking portions between respective pole pieces associated with each of the plurality of flux paths, to thereby establish magnetic fields having lines of force between the respective sets of pole pieces at angularly-spaced locations adjacent the target. Electrons are introduced to the respective magnetic fields transversely to the lines of force thereof for focusing upon the target from a plurality of angularly displaced directions. The flux densities in the respective linking portions of each flux path are then adjusted relative to each other, as by separately and controllably electromagnetically inducing flux in the respective linking portions, to provide a plurality of impact patterns of the electrons respectively focused from the plurality of angularly displaced directions. These impact patterns are angularly adjacent each other at the target and have configurations commensurate with the establishment of a composite impact pattern covering a predetermined area of the target. For example, where the target comprises material within an open-top cylindrical crucible and it is desired that the composite impact pattern cover the exposed surface of the material, in other words a circular surface area, the flux densities in the respective linking portions of each flux path are adjusted such that the electrons focused thereby form sectorial or triangular impact patterns on the exposed surface of the material with slight overlaps between the respectively adjacent ones thereof. Thus, the composite pattern is substantially circular and efficiently covers the exposed surface of the material.

It will be appreciated that the method outlined hereinbefore possesses substantial versatility in its application. The method embraces situations where the magnetic field is primarily included in a spatial region overlying a target such as the top of a crucible or the like, occupies a spatial region laterally adjacent the material to be treated, or has various other spatial dispositions relative to the target material to be treated. Furthermore, the electrons may be introduced to the field in any of its conceivable spatial dispositions from positions above, below, laterally of, etc., the target to be bombarded.

Considering now the bombardment heating guidance method broadly outlined hereinbefore in greater detail with respect to a specific application, and as to its conduct with one particular embodiment of apparatus, reference is again made to FIGURES 1 and 2, wherein the magnetic guidance field is established between pole pieces 29, 31 in a spatial region overlying crucible 14 and extending forwardly and downwardly from the top thereof, and wherein the electrons are directed from gun 26 into

the field from a location forwardly and downwardly from the top of the crucible. In this embodiment, controlled variation of the skewness of the magnetic lines of force is facilitated by adjustment of the relative flux densities in opposite sides of a low-reluctance flux path defined by the yoke 32, connecting the pole pieces 29, 31. In other words, the opposite sides or legs 34, 36 of the yoke define the linking portions of the flux path mentioned hereinbefore relative to the method. More particularly, where the flux density in leg 34 of the yoke is made greater than that flowing in leg 36, the lines of force extending between the pole pieces 29, 31 are skewed, or slanted, in the direction of the pole piece 29 associated with the leg portion 34 of greatest flux density. Conversely, when the leg 36 has a greater density of flux than the leg 34, the lines of force between the pole pieces are skewed in the opposite direction towards pole piece 31 associated with the leg 36 of greatest flux density. Moreover, when the flux densities in legs 34, 36 are equal, the lines of force between the pole pieces 29, 31 are substantially parallel to the web portion 33 of the yoke and accordingly possess substantially zero skewness.

Variation of the relative flux densities between the respective legs of the flux path is preferably facilitated by means of a pair of coils 37, 38 magnetically linked with separate legs. More particularly, coils 37, 38 may be advantageously concentrically disposed about core portions of the legs 34, 36 at the lower ends thereof adjacent the web 33 of the yoke. These coils are separately energized by power supplies 39, 41 appropriately connected to the coils such that upon energization, flux is induced in the respective legs of the yoke in additive directions. The densities of the flux induced in the respective legs is of course dependent upon the magnitudes of the currents separately applied to the coils. Thus, by controlling the relative magnitudes of the currents supplied to the coils, the relative proportions of the flux densities in the respective legs of the yoke may be correspondingly varied over a wide range to skew the lines of force between the pole pieces by substantially any desired amount in either direction.

The controlled skewing of the magnetic lines of force between the pole pieces in accordance with the present invention occurs principally in transverse planes extending longitudinally of the pole pieces. In other words, in the particular embodiment of the invention herein described and illustrated in the drawings, skewing of the field lines primarily occurs in transverse vertical planes between the pole pieces, as depicted in FIGURE 3. Skewing of the field lines to a lesser extent may also occur in transverse planes normal to the aforementioned transverse planes, that is in horizontal transverse planes between the pole pieces. To facilitate skewing of the field lines in the horizontal planes, the leg portions of the yoke are secured to the pole pieces at the vertical side edges thereof which are disposed adjacent the intermediate region of the crucible 14. The pole pieces accordingly include sections which project forwardly from the legs of the yoke. By virtue of this arrangement, skewing of the field lines in horizontal transverse planes between the pole pieces may be effected, which skewing could not be provided were the legs of the yoke to be secured to the midpoints of the pole pieces rather than to one side thereof.

It will be accordingly appreciated that with power supplies 39, 41 supplying equal currents to coils 37, 38 such that the flux densities in legs 34, 36 of the yoke 32 are equal, lines of force extend between the pole pieces 29, 31 as schematically depicted by the full lines of FIGURES 3 and 4. It is to be noted that the field lines are symmetrically disposed with respect to a vertical longitudinal plane of symmetry 42 substantially medially between the pole pieces (see FIGURES 3 and 4) as well as with respect to a vertical plane of symmetry 43 transversely between the pole pieces (see FIGURE 4). The

foregoing distribution of field lines with respect to planes 42 and 43 represents the condition of zero skewness mentioned hereinbefore. Now assume that power supply 39 is turned off, while supply 41 continues to energize coil 38. As a result, the flux density in leg 36 is greater than that in leg 34, and the lines of force between the pole pieces are skewed or slanted towards the pole piece 31 as depicted by the dashed lines in FIGURES 3 and 4. In both cases, electrons are emitted to the magnetic field from the electrode structure 27 of gun 26. The electrons are directed into the field transversely to the lines of force thereof, and in this regard the electrode structure 27 preferably includes one or more straight cathodes 44 parallel disposed with respect to the planes of symmetry 42, 43. It will be appreciated, that electrons entering the field traverse paths that at some time are perpendicular to the respective planes of FIGURES 3 and 4, and as viewed from these planes will move to impact perpendicular to the field lines. Thus, the impact pattern of electrons under the condition of skewed field lines as depicted by the dashed lines of FIGURES 3 and 4 will be moved towards pole piece 31 and the field pattern will be elongated in this direction compared to the position and configuration of the impact pattern with zero skewness of the lines of force as depicted by the full lines of FIGURES 3 and 4. Similarly, with the lines of force oppositely skewed in the direction of pole piece 29, the impact pattern of the beam will move or be elongated towards this pole piece. The precise resultant impact pattern configuration arising from skewing of the field lines cannot be readily predicted through a straightforward, mathematical analysis of single particle motion in magnetic fields in accordance with the well-known physical laws governing same. This is due to there being other factors involved when more than a single particle is to be considered, such as the coulomb forces between the respective electrons comprising the overall beam. However, it should be noted that through experimental observation, substantially any desired impact pattern may be produced depending upon the extent and direction to which the lines of force are skewed.

Where it is desired to sweep the impact pattern as noted relative to the method, the coils 37, 38 may be alternately energized by power supplies 39, 41. The flux densities in the respective legs 34, 36 of the yoke are thereby alternately maximized to skew the field lines alternately in opposite directions and thus sweep the impact pattern.

Although the pole pieces 29, 31 of the preferred apparatus of the invention may be provided as solid plates, same are more advantageously formed of a plurality of vertically-elongated, longitudinally-spaced bar segments 46. More specifically, the bar segments are fabricated of high-permeability material and are secured at their lower ends to a cross member 47 of the same material. The cross members 47 are in turn attached to the leg portions 34, 36 of the yoke 32. With the pole pieces thus provided in segmented form, a magnetic field may still be established between the pole pieces which is substantially similar to that established by solid pole pieces. However, by providing the pole pieces in the form of the spaced bar segments 46, the pole pieces may be more effectively cooled by virtue of the air spaces existing between the bar segments. Of more importance, the spaced-apart pole piece segments present minimized obstruction to the evacuation of the volume between the pole pieces. In applications where the pole pieces are disposed immediately adjacent the crucible or other container for holding molten material, such as in the case of the specific embodiments of FIGURES 1 and 2, this improved evacuation of the space between the pole pieces is highly desirable inasmuch as copious amounts of molecules, ions and the like are evolved to this spatial region from the molten material within the crucible or the like. Where the spatial region of the magnetic guidance field

is occupied by substantial amounts of gaseous materials of the foregoing type, the trajectories of bombarding electrons moving through the guidance field are detrimentally effected by collision processes occurring between the electrons and gaseous material, and the impact pattern of the electrons at the target surface may be undesirably distorted. With the segmented pole piece construction in accordance with the present invention the amount of gaseous matter within the space between the pole pieces is materially minimized by virtue of the more effective evacuation of same through the spaces between the pole piece segments and as a result the undesirable effects of electron collisions are greatly obviated.

The method of the invention may be alternatively conducted with the modified apparatus for generating a selectively skewable field illustrated in FIGURE 5. As shown therein, a plurality of pole pieces 48, 49, 51 are provided instead of the pair of pole pieces of the apparatus of FIGURES 1-4. Pole pieces 48, 49 are disposed in opposed transversely spaced relation, while pole piece 51 is disposed in spaced-parallel relation to pole piece 48 in a common longitudinal plane therewith. A yoke 52 of high permeability material is secured to the pole pieces to define a low reluctance flux path interconnecting same. More particularly, the yoke includes a web 53 interconnecting parallel legs 54, 56 projecting from the opposite ends thereof. The legs 54, 56 are, in turn, respectively secured at their free ends to the pole pieces 48, 51 at corresponding ends thereof and adjacent their outer longitudinal edges. The web 53 is secured to pole piece 49 in planar relation thereto, the pole piece projecting longitudinally from the web adjacent leg 54 at the opposite end of this leg from pole piece 48. Thus, leg 54 defines a linking portion of the yoke flux path between pole pieces 48, 49. Leg 56, with web 53, defines a linking portion of the flux path between pole pieces 49, 51. Likewise, legs 54, 56, together with web 53, define a linking portion of the yoke flux path between pole pieces 48 and 51.

To facilitate separate controllable variation of the flux densities in the respective linking portions of the flux path, a pair of coils 57, 58 are preferably concentrically disposed about the legs 54, 56. These coils are separately and controllably energized, as by means of variable direct current power supplies 59, 61 connected thereto. By varying the direction and magnitude of the currents supplied to the coils 57, 58 from the power supplies 59, 61, the flux densities in the linking portions of the flux paths respectively between the various pole pieces 48, 49, 51, are correspondingly varied. As a result, the lines of force of the magnetic field established between the pole pieces are skewed by varied amounts in either direction. More particularly, with power supplies 59, 61 energizing coils 57, 58 with currents flowing in appropriate directions to establish, for example, north poles at pole pieces 48, 51 and a south pole at pole piece 49, the lines of force between the magnetic field established between the pole pieces is substantially as indicated by the dashed lines of FIGURE 6. In this regard, it is to be noted that in transverse planes between pole pieces 48, 51, and pole piece 49, the magnetic lines of force are skewed downwardly towards the right (as viewed in FIGURE 6) in a region 62 of the space between the pole pieces, adjacent pole piece 49. The amount of skewing is, of course, dependent upon the relative magnitudes of the currents flowing in the coils 57, 58. Now, when the direction of current flow in coil 58, for example, is reversed to thereby establish a south pole at pole piece 51, north and south poles being still respectively established at pole pieces 48, 49, the magnetic lines of force in region 62 are skewed upwardly towards the right, as indicated by the dashed lines of FIGURE 7. Here again, the amount of skewing is dependent on the relative magnitudes of currents flowing in the coils. It will be thus appreciated that the amount and direction of skewing of the magnetic

lines of force in region 62 are readily controllably variable through appropriate adjustment of the currents supplied from power supplies 59, 61 to the coils 57, 58. Accordingly, where the field region 62 is established adjacent a target, and electrons are directed into the region transverse to the field lines, the impact pattern of the electrons upon the target is correspondingly varied as desired by controlled skewing of the field lines in the manner hereinbefore described.

While the present invention has been described hereinbefore with respect to several specific structural embodiments of the apparatus and as to specific steps in the method thereof, it will be appreciated that various changes and modifications may be made therein without departing from the true spirit and scope of the invention, and therefore it is not desired to limit the invention except by the terms of the following claims.

What is claimed is:

1. An electron beam furnace comprising an enclosure, means for evacuating said enclosure, material to be heated disposed within said enclosure, first and second pole pieces disposed in opposed spaced relation adjacent said material, a third pole piece disposed in a common plane with said second pole piece in parallel-spaced relation thereto, a yoke of high permeability material including a web with parallel legs projecting from its opposite ends, said legs respectively secured at their free ends to said second and third pole pieces, said web secured to said first pole piece, a pair of coils respectively linking said legs to establish upon energization a magnetic field having lines of force extending between said pole pieces, means disposed adjacent said pole pieces for directing electrons into said magnetic field transversely to said lines of force, and power supply means coupled to said coils for controllably separately energizing same to adjust the impact pattern of said electrons upon said material and control the heating thereof.

2. An electron beam furnace for controllably heating the surface of a target material disposed therein comprising, an enclosure, means for evacuating said enclosure, an electron gun disposed within said enclosure for generating a high intensity beam of electrons, means for establishing a unitary transverse magnetic field in the path of said beam of electrons, said unitary magnetic field establishing means including at least one pole piece on each side of said electron gun and a low-reluctance yoke interconnecting said pole pieces, and means for selectively inducing a variable magnetic flux in said pole pieces so as to provide magnetic lines of force of controllable direction of orientation extending between said pole pieces for focusing said beam of electrons upon the surface of said target material.

3. An electron beam furnace for controllably heating the surface of a target material disposed therein comprising, an enclosure, means for evacuating said enclosure, an electron gun disposed within said enclosure for generating a high intensity beam of electrons, means for establishing a unitary transverse magnetic field in the path of said beam of electrons, said unitary magnetic field establishing means including parallel-spaced pole pieces disposed on opposite sides of said electron gun, a low-reluctance yoke interconnecting said pole pieces, and magnetic windings magnetically coupled to said pole pieces for inducing magnetic flux therein, and means for selectively energizing said windings so as to provide magnetic lines of force of controllably, variable direction of orientation extending between said pole pieces, said direction of orientation of said lines of force being dependent upon the differential energization supplied to said windings, whereby the surface of said target material is controllably heated.

4. An electron beam furnace for controllably heating the surface of a target material comprising, an enclosure, means for evacuating said enclosure, an open-top con-

tainer disposed within said enclosure for holding the target material, means for establishing a unitary transverse magnetic field above the open top of said container, said unitary magnetic field establishing means including at least one pair of parallel-spaced pole pieces disposed on opposite sides of said container, said pole pieces extending outwardly from the open top of said container and forwardly of a peripheral portion thereof, a low reluctance yoke interconnecting said pair of pole pieces, and coils magnetically coupled to said pole pieces for inducing magnetic flux therein, power supply means for selectively energizing said coils so as to establish magnetic lines of force of controllable direction of orientation dependent upon the differential energization supplied to said coils by said power supply means extending between said pole pieces, and an electron gun having a straight cathode disposed at one side of said container and extending in the same general direction as said lines of force for injecting a beam of electrons transversely into said lines of force for focusing onto the top of said container thereby controllably heating the surface of the material therein by electron bombardment.

5. An electron beam furnace for controllably heating the surface of a material comprising, an enclosure, means for evacuating said enclosure, a crucible disposed within said enclosure for holding the material to be heated, means for establishing a unitary transverse magnetic field above the surface of said crucible, said unitary magnetic field establishing means including a pair of parallel spaced pole pieces disposed on opposite sides of said crucible and extending outwardly from the surface thereof and forwardly of a peripheral portion thereof, each of said pole pieces comprising a plurality of parallel spaced-apart pole segments, whereby the region between said pole pieces is efficiently evacuated by virtue of the provision of the spaced-apart pole segments, a low reluctance yoke interconnecting said pair of pole pieces, and coils respectively magnetically coupled to said pole pieces, power supply means electrically connected to each of said coils for selectively, separately energizing said coils, whereby magnetic lines of force of controllable direction of orientation dependent upon the differential energization supplied to said coils by said power supply means are established between said pair of pole pieces, and an electron gun disposed adjacent said crucible for injecting electrons transversely into said magnetic field, whereby said electron beam is controllably directed onto the surface of said material within said crucible.

6. An electron beam furnace for controllably heating the surface of a target material comprising, an enclosure, means for evacuating said enclosure, a crucible disposed within said enclosure for holding the material to be heated, means for establishing a unitary transverse magnetic field above the surface of said crucible, said unitary magnetic field establishing means including at least one pair of parallel-spaced pole pieces disposed on opposite sides of said crucible, said pole pieces extending outwardly from the open top of said crucible, and extending forwardly from an intermediate region thereof to a position beyond the periphery of said crucible, a yoke of high permeability material interconnecting said pair of pole pieces, and a pair of coils magnetically coupled to said pole pieces for inducing magnetic flux therein, a pair of D.-C. power supplies respectively connected to said coils for selectively, separately energizing said coils, thereby establishing magnetic lines of force of controllable direction of orientation dependent upon the differential energization supplied by said power supplies to said coils extending between said pole pieces, and an electron gun having an electron emitting element disposed between said pole pieces forwardly of said crucible and downwardly from the surface thereof for injecting electrons transversely through said lines of force for deflection along curved trajectories dependent upon the direction of ori-

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entation of said lines of force and onto the surface of said crucible, whereby said target material is controllably heated.

7. An electron beam furnace for controllably heating the surface of a target material disposed therein comprising, an enclosure means for evacuating said enclosure, an electron gun disposed within said enclosure for generating a high intensity beam of electrons, means for establishing a unitary transverse magnetic field in the path of said beam of electrons, said unitary magnetic field establishing means including at least one pair of parallel spaced pole pieces disposed on opposite sides of said electron gun, each of said pole pieces comprising a plurality of parallel-spaced-apart pole piece segments so as to facilitate the evacuation of the region between said pole pieces, and a low reluctance yoke interconnecting said pole pieces, and means for selectively inducing a variable magnetic

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flux in said pole pieces so as to establish magnetic lines of force of controllable direction of orientation extending between said pole pieces for focusing said beam upon said material.

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