

[54] APPARATUS AND METHOD FOR
DIRECTIONAL SOLIDIFICATION

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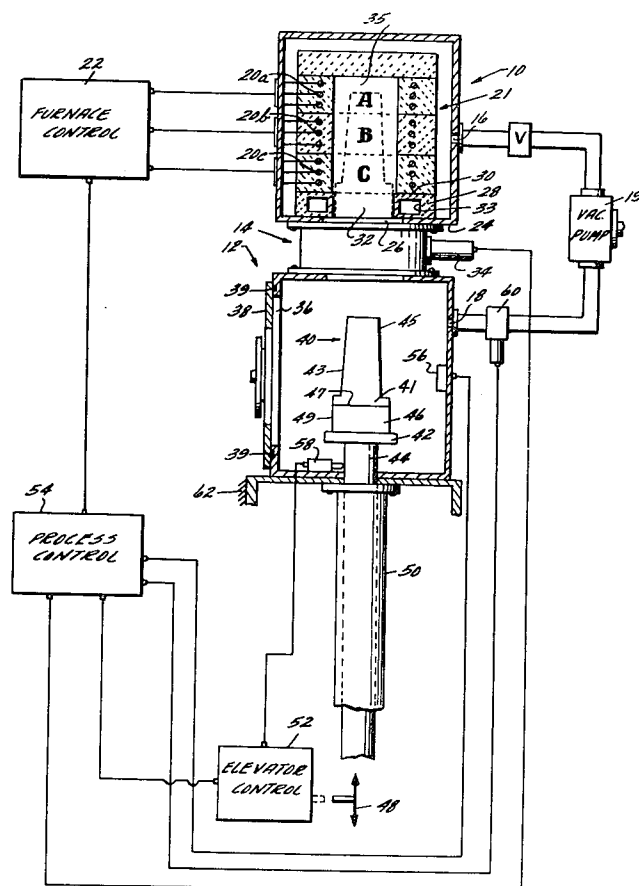
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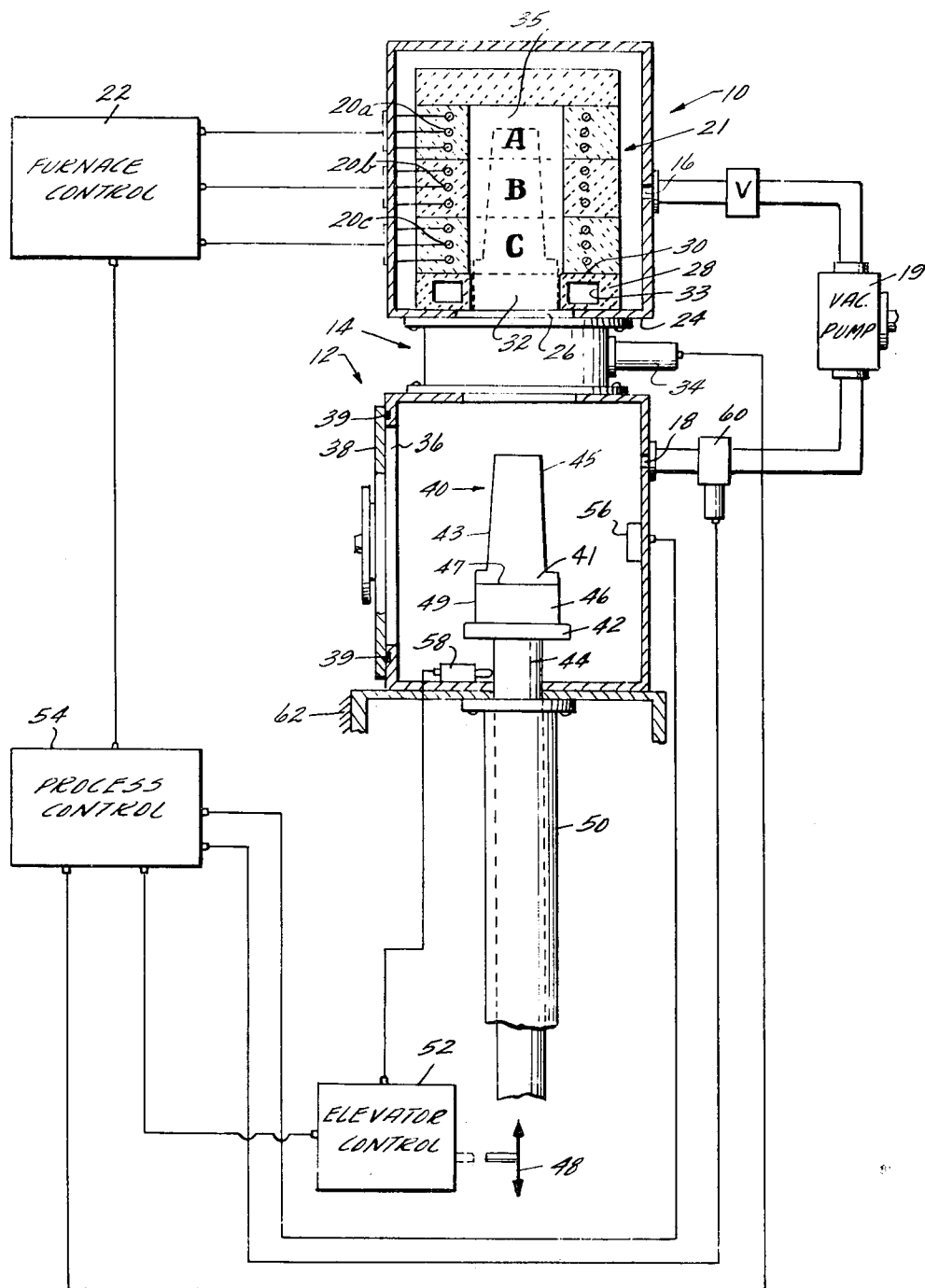
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[57] ABSTRACT

Control of manufacture of individual directionally solidified articles is provided by an improved apparatus, an important feature of which is a two-chamber vacuum casting furnace including a pair of cooperating chill members, a first being mounted in an upper chamber and a second being movable with a casting mold. Heating means applies heat to develop a plurality of heating zones within the furnace. The method practiced involves removing heat from metal in the mold initially predominantly through the first chill member and then through both chill members which are diverging one from the other. One chill member removes heat through the base of the casting being solidified while the other removes heat through the lateral walls of the casting predominantly at the liquid-solid interface traversing the solidifying casting.

7 Claims, 1 Drawing Figure





APPARATUS AND METHOD FOR DIRECTIONAL SOLIDIFICATION

The invention herein described was made in the course of or under a contract, or a subcontract thereunder, with the United States Department of the Air Force.

BACKGROUND OF THE INVENTION

This invention relates to casting of metal articles and, more particularly, to the casting of metal articles directionally solidified to include an elongated grain structure.

The advantages of providing an elongated, directionally oriented grain structure in a metal article through directional solidification include predominantly a significant advantage in thermal fatigue life over conventionally cast structures having an equiaxed grain structure. However, because current apparatus and methods, which have been well documented in the literature, generally have evolved from vacuum precision casting technology, relatively large, expensive and relatively difficult to control furnace apparatus has been used. In addition, shell cluster molds for casting of a plurality of articles from a single batch of poured molten metal have generally been employed.

A key to the efficiency and rate of production of directionally solidified articles is the control of heat transfer from the metal poured into the mold, through the mold and into other furnace apparatus. In general, a mold is positioned on a chill plate through which heat passes from the solidifying casting by conduction. If the mold is withdrawn from the heated zone of a furnace as in the "withdrawal method," heat transfer is enhanced by radiation into the unheated chamber into which the casting is drawn as the casting solidifies. However, accurate control of the position of the liquid-solid interface at which the grains are solidifying is important yet is difficult to achieve with reported apparatus.

SUMMARY OF THE INVENTION

It is a principal object of the present invention to provide, for the manufacture of a single directionally solidified article by the withdrawal method, an improved vacuum casting apparatus which includes improved chill members to more accurately control heat transfer from a mold chamber in which the article is being solidified.

Still another object is to provide such an apparatus including a furnace with heating means disposed to develop a plurality of heating zones to provide flexibility in heating desired portions of the furnace.

A further object is to provide an improved directional solidification method in which heat after casting initially is removed predominantly through a chill member which first contacts molten metal poured into a casting mold and then, in addition, through a second chill member about the mold lateral wall, the rate of withdrawal of the mold from the heated portion of the furnace being controlled to maintain the advancing liquid-solid interface preferable in the area of the top of the second chill member.

These and other objects and advantages will be more clearly understood from the following detailed description, the drawing and examples, all of which are in-

tended to be typical of rather than in any way limiting on the scope of the present invention.

In one more specific form, the present invention provides a vacuum casting enclosure which includes an upper and a lower chamber along with means to apply heat to the upper chamber. A vacuum valve can connect the chambers. The upper chamber includes a base having an opening which, through the vacuum valve, connects the upper chamber to the lower chamber and on which a first chill member is mounted. The first chill member includes a vertical chill passage through the member to allow passage of a mold through the chill member and through the base of the upper chamber. The lower chamber, which most conveniently includes an access port, also encloses a second, movable chill member including a portion which is sized to pass through the vertical chill passage of the first chill member after passing through the base of the upper chamber. Such second chill member is adapted to carry a casting mold. Means are provided to move the second chill member vertically between the two chambers. The apparatus also includes heating means which can be controlled to apply heat at various rates as desired within the upper chamber.

One form of the withdrawal method of the present invention includes removing heat from a molten metal filled mold initially at the mold bottom portion predominantly through a base chill member and then, as the mold is withdrawn, additionally through a chill member circumferentially disposed substantially about the mold and closely adjacent lateral portions of the mold. The rate of withdrawal of the mold from the heated upper chamber is controlled with the rate of heat transfer from the mold into the chill members to maintain the liquid-solid interface of a solidifying metal article within the mold in the area of the top surface of the first chill member and generally just above such surface. It should be understood that as used herein, the term "metal" is intended to include metal alloys.

BRIEF DESCRIPTION OF THE DRAWING

The drawing is a partially sectional, partially diagrammatic view of one form of the apparatus involving the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Development of the withdrawal method for manufacturing directionally solidified articles eliminated a number of problems which had existed in connection with earlier developed methods. In general, the withdrawal method involves placing a hot ceramic shell cluster mold on a chill plate mounted on an elevator mechanism. As the solidification zone starts to move upward by conduction of heat to the chill plate, the mold is withdrawn from the hot zone of the furnace at a predetermined rate into an unheated chamber or portion of the furnace. Heat transfer by conduction through the chill plate at the base of the mold is then enhanced by radiation toward walls of the unheated chamber. As the mold is withdrawn, the conductive path through the solidifying casting to the chill plate is increased to a point at which its effectiveness is greatly reduced. Then radiation from the solid portion of the casting drawn into the unheated chamber is the mechanism relied upon to maintain the thermal gradient at the liquid-solid interface within the casting mold. However, this basic

method is lacking in its ability to maintain in a very precise manner a maximum thermal gradient at the solidifying interface throughout the total cycle. One reason is that a cluster mold, including cavities for a plurality of articles to be cast from a single pour of molten metal, is used. In addition, precise control of heat transfer from the mold has not been provided.

The furnace involved with the present invention provides capability for attaining such maximum thermal gradient through a combination of a plurality of chill members along with precise, selective heat application. The plurality of chill members includes one which during withdrawal closely surrounds a single mold. Another, on which the mold is mounted, constitutes a base chill plate movable with the mold and through which heat is conducted from the metal from which the article is being made.

The drawing shows one form of the apparatus in a partially sectional, partially diagrammatic view. The vacuum casting apparatus involving the present invention includes an enclosure shown in the embodiment of the drawing to have an upper chamber shown generally at 10, a lower chamber shown generally at 12 and a vacuum valve shown generally at 14 connecting the upper and lower chambers. Associated with the upper and lower chambers are means to evacuate such chambers such as through ports at 16 and 18. Such means can, for example, include a common vacuum pump 19, or individual pumps, to create a vacuum within the upper chamber and lower chamber as desired.

Within upper chamber 10 is a furnace shown generally at 21, and including heating means shown in the drawing to be three vertically stacked individual resistance windings 20a, 20b and 20c as heat sources. Each winding is powered from a source of electrical energy and is controlled through a furnace control means 22 which can vary the power input to each source. Control means 22 also can coordinate the rate of heat applied by each heat source to the hollow interior of chamber 10 through the use of standard variable power control apparatus commercially available and well known in the electrical art. Although the heating means which applies heat to the furnace in the upper chamber is shown as a resistance-wound three-part unit, it will be understood by those skilled in the art that a variety of means of applying and controlling heat might be used to accomplish the intended thermal control in the various zones involved.

One important feature of the present invention is that the furnace walls formed by the heating means and which together define a furnace hollow interior 35, are disposed closely adjacent and substantially enclose a casting mold lateral and top portions. This arrangement, along with the heating means, provides more accurate control of the metal within the mold, particularly at the start of the method involved with the present invention. The furnace walls enclosing the heating elements generally are of a ceramic material such as alumina.

Upper chamber 10 includes a base 24 having an opening 26 therethrough to enable communication between upper chamber 10 and lower chamber 12 through vacuum valve 14. Mounted on base 24 is a circumferentially disposed first chill member 28 which includes a top surface 30 and a vertical chill passage 32 through the first chill member and aligned with upper chamber base opening 26. The first chill member is

preferably metal, for example, copper or a copper-base alloy, and preferably includes means diagrammatically represented as conduit 33 associated with a cooling fluid source (not shown) to circulate a cooling fluid through the chill, for example water, to enhance the heat transfer through the first chill member. Such cooling means can be disposed as cooling coils within or around the chill in a manner well known in the art, for example, in connection with water-cooled heat transfer members.

In order to allow intercommunication between upper chamber 10 and lower chamber 12, vacuum valve 14 includes a means 34 to operate vacuum valve 14. Vacuum valve 14 and means 34 are of a type commercially available, well known and widely used in the vacuum furnace art involving multiple compartment furnaces. Through the use of such a vacuum valve, upper chamber 10 can be environmentally isolated from lower chamber 12 to maintain in upper chamber 10 a vacuum, once it has been developed there, while lower chamber 12 is used for loading and unloading molds before and after operation.

Lower chamber 12 has an access port 35 which includes a door 38 having associated vacuum sealing means 39. Access port 36 can be of any convenient shape, for example to accommodate loading or unloading of a casting mold, such as of ceramic shown generally at 40. Mold 40 includes a foot or base 41, lateral walls 43 and top portion 45.

Shown in lower chamber 12 is a mold platform 42 operatively connected with a vertically operating elevator mechanism 44 adapted to raise and lower mold platform 42 toward and away from upper chamber 10. Mounted on mold platform 42 is a second chill member 46, movable with the mold platform, and having a top surface 47 on which casting mold 40 is mounted. This is one example of means to provide relative movement between the chill members 28 and 46 and hence such movement between mold 40 and first chill member 28.

Second chill member 46, sometimes referred to as a base, preferably is metal and can be fluid cooled in a manner similar to the first chill member. The second member is shaped to pass into vertical chill passage 32 of first chill member 28 in upper chamber 10, for example, by having its lateral wall 49 shaped to a slightly smaller configuration of chill passage 32. Accordingly, elevator mechanism 44 has a vertical stroke sufficient to raise second chill member 46 into vertical chill passage 32, thus to enable positioning of casting mold 40 within upper chamber 10, as is shown in phantom in the drawing. Elevator 44, which can be a machine screw type mechanism driven by a reversible rotating means such as a reversible motor diagrammatically represented by arrows 48, is housed within a jacket 50 including appropriate vacuum sealing means to isolate lower chamber 12 from the atmosphere.

Associated with rotating means 48 is an elevator control 52 capable of initiating and terminating the operation of rotating means 48 and, if desired its speed. In a more automated form of the present invention, elevator control 52 is coordinated with furnace control 22, in a manner which will be described in more detail in connection with one form of the method associated with the present invention. This can be accomplished through process control means 54, one principal function of which is to time the heat applied in upper chamber 10 through furnace control 22 with the rate of with-

drawal of casting mold 40 from furnace 21 through elevator control 52. In a still more automated form of the apparatus involving the present invention, coordinating process control means 54 can initiate operation of means 34 to operate vacuum valve 14 as a function of a signal from a pressure sensor 56 within lower chamber 12 signalling control means 54 that an adequate vacuum has been provided within lower chamber 12 to enable opening of vacuum valve 14. In addition, control means 54 can be programmed to close valve 34 as a function of the position of casting mold 40 being withdrawn from upper chamber 10 and passing through vacuum valve 14. In one form, such sensing means can be a commercially available proximity switch 58 in lower chamber 12 and a similar switch (not shown) in upper chamber 10 to sense the position of mold 40 such as through mold platform 42. A further function which can be performed by coordinating control means 54 is to initiate production of a vacuum, or to release the vacuum, within lower chamber 12, for example as a function of the sealing of access port 36 or of the mold position. For example, this can be accomplished through a valve 60 associated with lower chamber evacuation port 18 to provide evacuation of the lower chamber.

The vacuum casting furnace can be supported in a variety of ways, as those skilled in the art will recognize. A support member 62 is shown diagrammatically in the drawing to represent support means. The location of a single furnace or an arrangement of a plurality of such vacuum casting furnaces, which with its controls each defines a furnace module, may suggest a particular support means most useful to one skilled in the art.

The close control for directional solidification provided by the present invention is accomplished in part by applying heat within furnace 21 at a plurality of rates to accomplish different functions. For example, heat is applied to the interior of furnace 21 in amounts first to melt a solid metal charge and then to maintain the temperature of melted metal within casting mold 40 at a temperature greater than its melting temperature, except that perhaps for a relatively small area at the base of the mold in which solidification is occurring. The present invention is particularly adapted to use a self-casting mold, for example of the type described in co-pending application Ser. No. 411,927, filed concurrently with this application. Therefore, one form of the method associated with the present invention requires heat application to achieve the highest temperature in the mold in the top zone of the furnace, indicated at A, in order to bring about as rapid alloy charge melting as possible. If desired, further variation of heat application within a zone such as top zone A can be provided for more selective control of charge melting. Because of the heat carried away by chill member 30, heat application to the lower zone, indicated at C, is relatively high compared with intermediate zone, indicated at B, in order to maintain metal within the mold above its melting temperature, except below the liquid-solid interface near the base of the mold at which directional solidification initially is occurring. Thus, the present invention includes the application of heat to the furnace interior at a plurality of rates to control more closely the casting and then the directional solidification of the metal within the mold as the method proceeds. As was mentioned before, the close control af-

forded by such variable application of heat in the zones described is enhanced by disposing the furnace walls closely adjacent and substantially enclosing the casting mold lateral and top portions.

After sufficient temperature is generated in zone A of the furnace to melt the alloy charge and allow it to flow into the bottom part of the mold, heat is removed from the mold initially through the base chill member, indicated at 46 in the drawing. Chill member 46, at the beginning of the method, is disposed within vertical chill passage 32 of the first chill member 28 shown in the drawing to be circumferentially disposed about and closely adjacent the path the mold traverses. Then, as the mold is withdrawn from furnace 21 as a result of the downward movement of elevator mechanism 44, heat is withdrawn through the base chill member 46 as well as through the chill member 28 which becomes disposed substantially about a lateral portion or circumference of mold 40. Practice of the method includes coordinating elevator control 52 with furnace control 22 to maintain the liquid-solid interface of the directionally solidifying alloy within mold 40 in the vicinity of the top surface 30 of the first or circumferentially disposed chill member 28. This improved control of heat flow through the practice of the present invention, employing the plurality of chill members diverging one from the other but disposed at those areas of the mold requiring the closest heat flow control, eliminates casting defects such as stray equiaxed grains, freckles, mis-oriented grains and shrink.

Referring to the drawing, one form of the method involved in the present invention is practiced by first closing vacuum valve 14 while elevator mechanism 44 and platform 42 are disposed substantially as shown in the drawing within lower chamber 12. A vacuum is then provided in upper chamber 10 and furnace 21 through upper chamber port 16 and vacuum pump 19. A self-casting mold 40, including a solid metal charge in its upper portion, is secured to base or second chill member 46. Access door 38 is closed and sealed after which lower chamber 12 is evacuated through port 18 and a vacuum pump such as 19. As was mentioned before, the closing and sealing of door 38 can signal valve 60 to initiate creation of the desired vacuum in lower chamber 12. Such pressure level can be sensed by pressure sensor 56 which can then signal process control 54 to operate means 34 to open vacuum valve 14. Thereafter, process control 54 can signal elevator control 52 to raise mold 40 to the position shown in phantom in the drawing as sensed by a proximity switch appropriately located. In any event, this form of the method of the present invention basically includes providing an appropriate vacuum in lower chamber 12, opening vacuum valve 14 and elevating mold 40 into position within furnace 21.

With the mold in the position shown in phantom in the drawing, heat applied at a high rate, primarily as a result of heating means 20a, raises the temperature of the solid metal charge in the top portion of the mold above its melting temperature. The molten charge then flows downwardly by gravity filling the lower portion of the mold in which an article is to be generated. At the same time, heat is applied through heating means 20b, and at a higher rate through heating means 20c, to maintain the cast charge above its melting point except in the area of top surface 30 of the circumferentially disposed first chill member. Elevator control 52 is then

activated to lower mold 40 from furnace 21. However, the rate of withdrawal is coordinated with the heat applied through furnace control 22 to the various zones within furnace 21 to maintain the liquid-solid interface of the directionally solidifying metal within the mold in the general area of the top surface 30 of the first chill member 28 circumferentially disposed about the withdrawing mold. In this way, the liquid-solid interface traverses the mold at a closely controlled rate to provide a directionally solidified article of improved quality.

After complete withdrawal of mold 40 from furnace 21 in upper chamber 10 into lower chamber 12, vacuum valve 14 is closed to maintain vacuum in upper chamber 10. Closing of valve 14, such as through means 34, can be accomplished as a result of a signal, such as from a proximity switch, to process control 54 which directs such closure. Vacuum is then released from lower chamber 12, such as by opening valve 60, manually or on signal from process control 54. Access door 38 is then opened, mold 40 is then removed, and the apparatus is ready for another cycle.

Although the present invention has been described in connection with specific examples and embodiments, it will be understood by those skilled in the art, the variations and modifications of which the invention is capable within its broad scope.

What is claimed is:

1. In a method for directionally solidifying an article in a casting furnace from a molten metal cast into a casting mold having a mold foot and outer lateral walls, wherein heat is first removed from the molten metal through cooling means connected with the mold foot and then heat is removed concurrently through the mold foot and the lateral walls by causing relative motion between the mold and a chill member to move a solidifying metal zone through the mold, the chill member having a central opening defined by a chill wall and a chill top surface;
the improvement comprising, in combination, the steps of:
providing the chill member with a chill wall and the casting mold with an outer lateral wall, each of said walls configured to be closely adjacent one to the other during the relative motion between the mold and the chill member, with the chill wall circumferentially disposed about the outer lateral wall, the lateral wall enclosing a single article casting chamber communicating with the mold foot;
causing molten metal to be deposited in the casting chamber with the mold foot closely adjacent the chill wall at the chill top surface; while at the same time,
applying a first amount of heat selectively toward the mold outer lateral wall in a first furnace area immediately above the chill top surface to heat the wall when in the first area sufficiently to maintain the metal in substantially the molten state; and concurrently,
applying a second amount of heat, less than the first amount but sufficient to maintain the metal in substantially the molten state, selectively toward the mold outer lateral wall when in a second furnace area above the first area; while,
removing heat from the metal progressively during relative motion between the mold and the chill member through the means connected with the mold foot and through the chill wall at a rate suffi-

cient to substantially solidify the metal as it traverses adjacent the chill top surface.

2. The method of claim 1, for use with a casting mold of the self-casting type having a top portion adapted to hold a solid metal charge, in which:

the molten metal charge is deposited in the casting chamber by applying concurrently with the first and the second amounts of heat, a third amount of heat in a third furnace area toward the mold top portion holding the solid metal charge, the third amount of heat being greater than the second amount and less than the first amount but sufficient to melt the solid metal charge.

3. Vacuum casting apparatus including:

walls defining an enclosure having an upper chamber and a lower chamber;

evacuating means to evacuate the upper and lower chambers;

isolating means to environmentally isolate the upper and lower chambers one from the other;

a first chill member having a chill passage through and located within the upper chamber;

a second chill member within the enclosure sized to pass into the chill passage and adapted to carry a casting mold;

means to move the second chill member between the lower chamber and the first chill passage; and
heating means comprising a plurality of elements in substantial vertical array to heat the upper chamber;

the improvement wherein:

the heating means includes a vertically stacked plurality of separately controlled heat sources, each positioned substantially vertically above the first chill member, the heat sources having interior surfaces substantially aligned with each other and with the chill passage to define a hollow furnace interior adapted to receive a casting mold with a single article casting cavity enclosed by lateral walls, the interior surfaces being positioned closely adjacent and substantially enclosing the mold lateral walls during operation;

the apparatus including furnace control means operatively connected with each heat source and including means for applying heat concurrently at a plurality of rates and for varying the intensity electrical power to each heat source independent of the other heat sources.

4. The apparatus of claim 3 in which the furnace control means is adapted to apply a relatively larger amount of electrical power to a first of the heat sources adjacent the first chill member concurrently with the application of a relatively smaller amount of electrical power to a heat source above the first heat source.

5. The apparatus of claim 3 which includes, in addition:

process control means to coordinate the rate of heat application to the hollow furnace interior through the furnace control means with the means to move the second chill member between the lower chamber and the first chill passage.

6. The apparatus of claim 5 in which the process control means is operatively connected with the isolating means to coordinate movement of the isolating means with the furnace control means and the means to move the second chill member.

7. The apparatus of claim 6 in which the process control means also is operatively connected with the evacuating means to coordinate the evacuating means with the isolating means.

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