United States Patent [19]

Hunt

[11] **3,709,284**

[45] **Jan. 9, 1973**

[54] **APPARATUS FOR CONTINUOUS CASTING**

[75] Inventor: **Charles d'A. Hunt,** Moraga, Calif.

[73] Assignee: **Airco, Inc.**

[22] Filed: **Nov. 19, 1971**

[21] Appl. No.: **200,625**

Related U.S. Application Data

[62] Division of Ser. No. 44,130, June 8, 1970, Pat. No. 3,658,116.

[52] **U.S. Cl.** **164/281,** 164/120, 164/321

[51] **Int. Cl.** **B22d 11/10**

[58] **Field of Search**....164/82, 85, 89, 120, 273, 281, 164/283, 319, 320, 321

[56] **References Cited**

UNITED STATES PATENTS

3,620,686	11/1971	Pfann	164/82 X

FOREIGN PATENTS OR APPLICATIONS

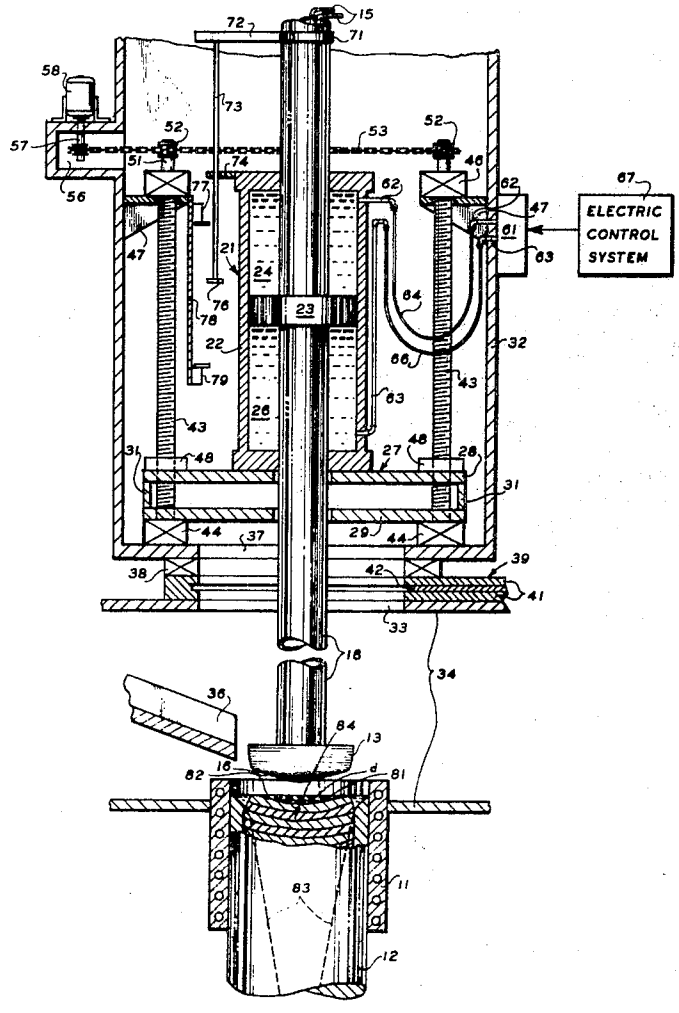
188,803	11/1922	Great Britain	164/85
1,107,900	5/1961	Germany	164/82
258,977	11/1963	Australia	164/89

Primary Examiner—Robert D. Baldwin
Assistant Examiner—John E. Roethel
Attorney—Fitch, Even, Tabin & Luedeka

[57] **ABSTRACT**

Apparatus is described for continuously casting an ingot wherein a cooled plug is repeatedly brought into contact with the top of the ingot during the continuous casting process to remove heat from the central region of the ingot.

5 Claims, No Drawings



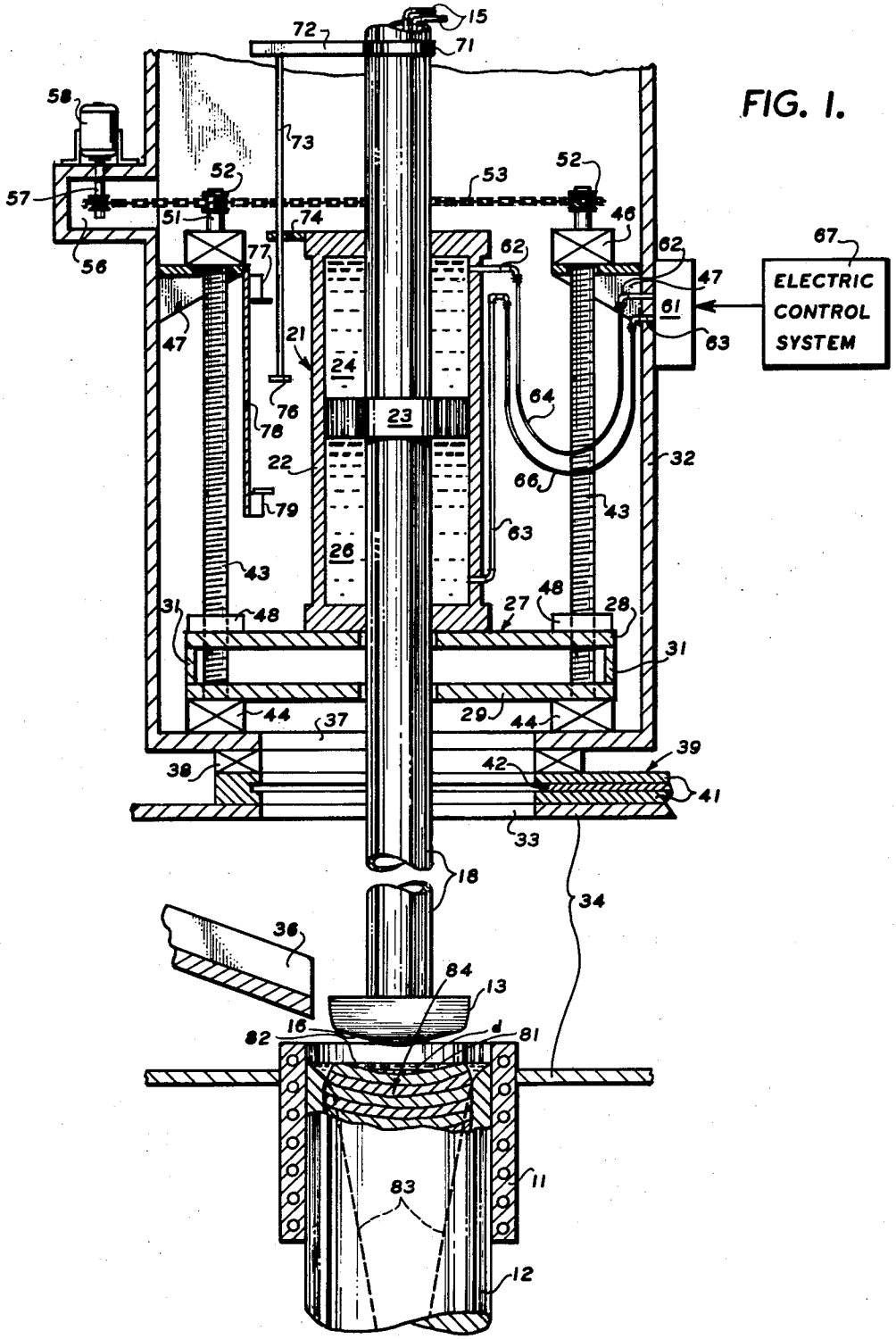


FIG. 1.

FIG. 2.

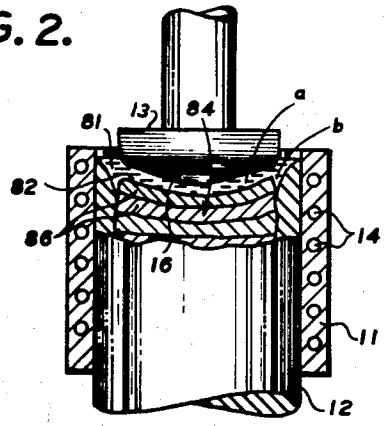
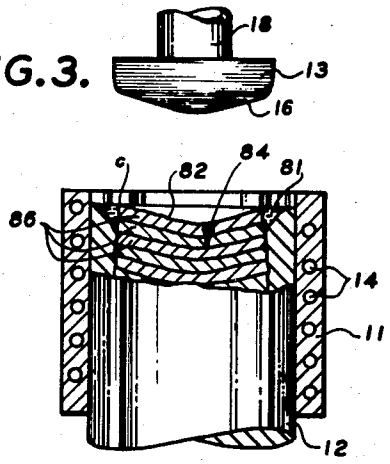


FIG. 3.



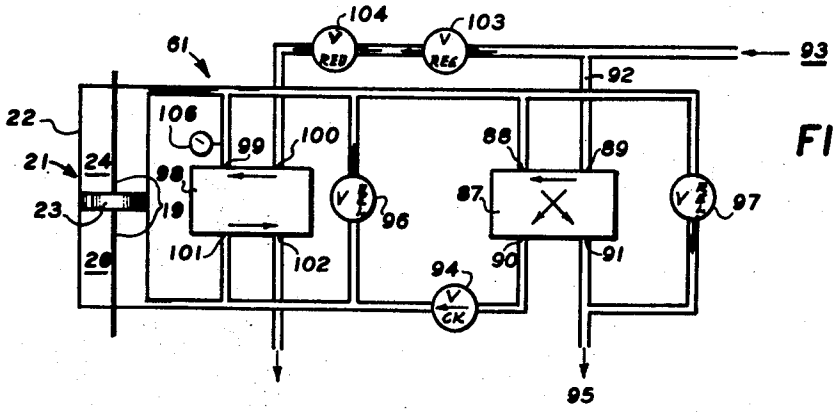
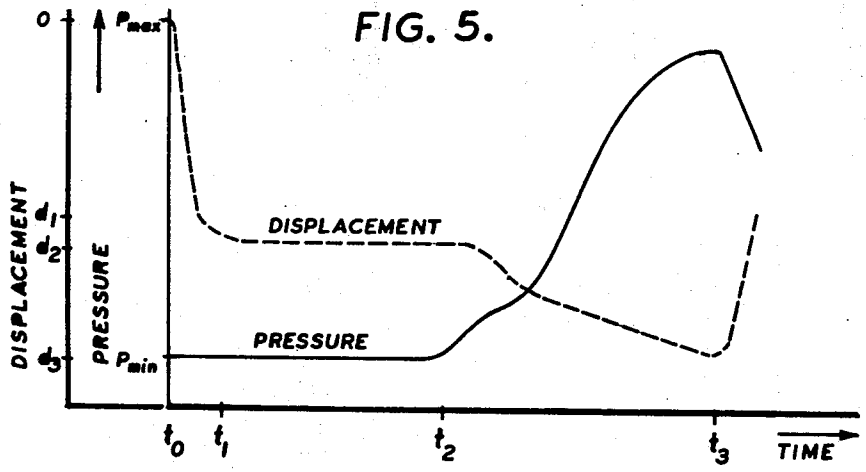


FIG. 4.

FIG. 5.



APPARATUS FOR CONTINUOUS CASTING

This application is a divisional application of application Ser. No. 44,130, filed June 8, 1970, now U.S. Pat. No. 3,658,116, and assigned to the assignee of the present invention.

This invention relates to the continuous casting of metal ingots and, more particularly, to a method and apparatus for continuously casting an ingot wherein problems of segregation are minimized.

The process of continuously casting metal ingots is well known and widely used in industry. Generally, the continuous casting process employs a casting mold having a cooled outer wall and a movable bottom or plug. Molten metal is poured into the open top of the mold and, as the metal solidifies in the mold, it is drawn downwardly by the plug while at the same time additional molten metal is poured into the mold at the top. The mold is of sufficient length and the casting rate is sufficiently slow to allow the outer annular region of the ingot to solidify enough to prevent breakout or enlargement due to the pressure of the internal metal which may still be molten. The process is continued until the supply of molten metal is depleted or otherwise cut off and the solidified ingot is then drawn downward until it is completely removed from the mold.

For certain materials, such as highly alloyed tool steels, bearing race steels, and many high temperature service nickel base alloys, segregation problems may occur in continuously cast ingots. For example, serious segregation of carbides or carbonitrides may develop and show up as relatively large nodules (freckling), continuous films, or elongated rods, all of which are difficult to break up and redistribute into solution by forging or heat treatment in subsequent stages of the material processing. Another type of segregation, known as coring, may develop between the majority elements of the alloy. This problem is manifested by a difference in concentration of the majority elements within each crystal or grain of the ingot between the last intracrystalline areas to freeze and the first intracrystalline areas to freeze. In other words, as a crystal or grain freezes, dendrites grow inward from the grain boundary and enlarge. Segregation may occur along the dendrite-liquid interface resulting in coring. Prohibitively large annealing times may be required to diffuse the majority elements to a more uniform distribution within the grains.

A third type of segregation problem may occur, which is similar to coring but which occurs over distances of several inches rather than within the intracrystalline structures. This third problem may occur with the majority elements, but may also occur with elements such as sulphur or phosphorus, and results in a variation in alloy constituents or in phosphor or sulphur content in different regions of the ingot. Such a problem typically occurs where certain regions of the ingot, usually the center, cool very slowly with respect to other regions.

In order to avoid segregation problems such as are described above in continuously cast ingots, the solidification rate may be maintained at a sufficiently high level. The solidification rate may be controlled by controlling the casting rate or the cooling rate of the ingot. Higher solidification rates and hence a fairly

rapidly moving liquid-solid interface during the liquid solid transformation will minimize the development of carbide and carbonitride segregation by shortening the time available for nucleation and buildup of higher melting point segregates. Moreover, a high solidification rate with accompanying high liquid-solid interface movement produces relatively small secondary dendrite arm spacing (of the order of 1 to 10 microns). Diffusion of the alloy constituents is thereby possible over relatively small distances and therefore can take place in correspondingly shorter times at appropriate annealing temperatures. In addition, alloy composition gradients existing between dendrite arms in interdentritic spaces are maintained relatively small with small secondary arm spacing because the faster solidification time allows less time for solute redistribution. This again enables a shorter time at the annealing temperature. Finally, the rapidly moving liquid-solid interface with its consequently shorter solidifying zone minimizes the production of compositional variation in majority elements over large distances.

In order to maintain a high solidification rate and thereby maintain a rapid liquid-solid interface movement during the liquid-solid transformation, appropriate cooling may be provided for the ingot as it is drawn downwardly below the mold. Systems for providing such cooling may employ water sprays, baths of molten salts, or other appropriate means to increase the solidification rate by providing modes of heat transfer in and below the ingot mold in addition to the radiation mode. Where, however, a large diameter ingot is economically desirable to provide a higher casting rate, or where additional modes of heat transfer are inconvenient, such as is often the case in continuous casting processes in vacuum, heat extraction through the ingot by conduction into the mold and heat extraction from the ingot to the region below the mold, is relatively constant and non-controllable, at least in the central region of the ingot.

To avoid segregation problems under the circumstances outlined above, the ingot may be cast at a rate which is sufficiently slow. To do this, the heat input to the ingot from molten material flowing into the top of the mold is made sufficiently less than the level of the relatively constant heat extraction from the ingot that a solidification rate which maintains segregation within tolerable limits is achieved. Where production requirements dictate high casting rates, however, a very deep molten pool may result in the ingot, especially one of large diameter, with resultant slow solidification in the central region of the ingot and a subsequent segregation problem.

It is therefore an object of the present invention to provide an improved method and apparatus for continuous casting.

Another object of the invention is to provide a method and apparatus for continuous casting which alleviates segregation problems.

It is another object of the invention to provide an improved method and apparatus for removing heat from continuously cast ingots during the casting process.

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 sectional view illustrating apparatus constructed in accordance with the invention;

FIGS. 2 and 3 are partial sectional views illustrating different steps in the operation of the apparatus of the invention;

FIG. 4 is a circuit diagram of a hydraulic control system which may be used in the invention; and

FIG. 5 is a graph illustrating operating characteristics of the apparatus of the invention.

Very generally in practicing the invention, molten metal is introduce into a cooled continuous casting mold **11** and the cast ingot **12** is pulled downwardly through the mold. The molten pool at the top of the ingot is repeatedly contacted, at the central region thereof, with a cooled plug **13** to remove heat from the central region of the ingot.

In practicing the method of the invention, higher casting rates are achieved by removing heat from the central region of the ingot at the top thereof. This is done by repeatedly contacting the molten pool at the top of the ingot in the central region by the cooled plug. The diameter of the region contacted by the cooled plug is preferably not less that about 8 inches smaller than the diameter of the ingot (or the distance across the flats in the case of a round corner square ingot). This ensures that the depth of the annular molten pool between the solidified central section and the solidified outer wall of the ingot will not be so great that solidification rates in the middle of the pool are slower than those desired. Preferably, the area of the plug which contacts the ingot is of sufficient size as to extend completely out to the area where rapid freezing occurs due to cooling from the mold walls. This ensures that the depth of the molten pool will be substantially uniform across the entire cross section of the ingot. If the plug is too small and too little heat is removed, a central post forms in the central region of the ingot which is undercut by the superheat provided by the added molten material. Once the central post is undercut, the top of the solidified post will pull away with the plug when the plug is removed. On the other hand, if too much heat is removed, cold shuts will result on the outer surface of the ingot and moreover the new metal being added at the top of the ingot may make an unsatisfactory weld to the existing solidified metal.

As mentioned before, it is preferred that the size of the plug be sufficient to contact the ingot in the central region over an area which extends all the way out to where rapid solidification of molten material occurs due to cooling from the mold walls. Typically, this is within one or 2 inches from the inner surface of the mold. The plug is left in contact with the ingot long enough to freeze or solidify most of the metal under the plug and is maintained out of contact with the ingot for a period of time long enough to allow additional molten metal to flow into the region which has just solidified. The actual optimum times may be determined empirically depending upon the various heat transfer characteristics of the system and the characteristics of the particular metal being cast. Nevertheless, in-contact times for many metals typically run in the range of about 3 to 10 seconds for best results, and typical out of contact times run in the range of about 2 to 6 seconds. Ideally, the system operation should be balanced so that the in-contact time is the maximum attainable and the out of contact time is only sufficient to let a thin layer of new molten metal run into the contacted region. Generally speaking, the thinner the laminates of layers of molten metal which are contacted with each repetition, the finer the metal grains and the less the segregation problems. It is preferable that the depth of each lamination or each new layer of molten metal not exceed ½ inch when spread out due to contact of the cooled plug.

To effect the desired degree of heat removal, the plug is brought into contact with the ingot with a substantial amount of force. This ensures that adequate heat transfer will take place and, moreover, effects a substantial amount of hot working of the partially solidified material. This pushes voids in the material closed, and mechanically feeds the natural shrinkage cavities around dendrites where the normal hydrostatic pressure of the melt is inadequate. The working also interrupts the formation of nucleated carbides or carbonitrides. Moreover, the more rapid cooling which is effected causes fast moving of the liquid-solid interface so that a deep molten pool is not produced, thereby keeping the freezing zone relatively small. Thus, segregation resulting from the particular kinetics of solidification of a given material is avoided by the method of the invention by producing conditions in which any tendency toward nucleation is interrupted and broken up and in which the freezing time is vary rapid and the freezing zone very small. In other words, there is accomplished high heat removal from a relatively small volume.

The method of the invention may be more fully understood in connection with the apparatus of the invention and by referral to the accompanying drawings. The invention is illustrated therein in connection with continuous casting in a vacuum system, for example, such as is shown and described in U. S. Pat. No. 3,343,828 assigned to the present assignee. The invention is applicable, however, to other casting systems including those operating at atmospheric pressure.

The continuous casting mold **11** in FIG. 1 is provided with a plurality of passages **14** therein through which a suitable fluid coolant, such as water, is circulated. This removes heat from the material in the mold thereby solidifying the ingot **12**. The lower end of the ingot **12**, not shown, is attached to a suitable puller or plug, not shown, to be drawn downwardly through the mold **11**. Attachment to the puller is usually effected by allowing the molten metal to solidify around a dovetail type connection on the plug when the casting is started, as is known in the art. The illustrated ingot is cylindrical, however, other shapes may also be cast in accordance with the invention, one common ingot shape being the so-called round corner square ingot.

The plug **13** as illustrated has a conical lower surface **16**. The plug **13** is suitably secured to the lower end of a ram **18**. The upper end of the ram **18** comprises the piston rod **19** of a hydraulic cylinder **21**. The ram and piston rod are hollow to accommodate coolant ducting **15** for cooling the plug **13**. The hydraulic cylinder **21** includes an outer housing **22** and an internal piston **23** dividing the interior of the housing **22** into an upper chamber **24** and a lower chamber **26**. The hydraulic cylinder **21** is mounted on and supported by a bridge structure **27** constructed of an upper plate **28**, a lower plate **29**, and a plurality of vertical members **31** joining the upper and lower plates to form a rigid assembly.

The hydraulic cylinder 21 and the bridge 27 are contained within a vacuum tight enclosure 32. The enclosure 32 is mounted over an opening 33 in the upper wall of the main vacuum tank 34. A launder 36 is provided within the tank 34 for conveying molten metal into the mold from elsewhere in the vacuum system. The molten metal may be poured into the ingot intermittently or continuously. The enclosure 32 has an opening 37 therein and is mounted over the top of the vacuum tank about the mold with the opening 37 aligned with the opening 33 in the tank. An annular vacuum seal 38 and a gate valve 39 are positioned between the enclosure 32 and the top of the main vacuum tank 34. The gate valve 39 includes a main housing 41 and a slidable seal plate 42 which is retractable to the position shown when the enclosure 32 is in place and is pumped down, and which is movable to a closed position within the valve housing 41 when it is desired to retract the ram and remove the apparatus for repair or replacement.

In order to be able to retract the ram and the plug 13 attached thereto from the main vacuum tank 34 through the opening 33 therein, the bridge 27 is supported for vertical movement. Four vertical screws 43, two of which are shown in FIG. 1, are supported on the floor of the enclosure 32 by bearings 44. The upper ends of the screws 43 are journalled in bearings 46 supported on brackets 47 which are mounted to the sidewalls of the vacuum tight enclosure 32. The bridge 27 is provided with four internally threaded collars 48, one for each of the screws 43. The screws 43 are in threaded engagement with the collars 48 and pass through the bridge 27 through suitable openings, not shown, provided in the bridge. The four screws 43 are rotated simultaneously by means described below to cause the bridge to move upwardly and downwardly within the enclosure 32. In FIG. 1, the bridge is shown in its lowermost position, which is the position in which the apparatus is normally operated. When it is desired to remove the ram 18 and plug 13 from the vacuum chamber, the screws 43 are rotated to move the carriage of bridge 27 to its uppermost position, with the upper plate 28 of the bridge just beneath the brackets 47. In this position, the ram 18 and the plug 13 may be moved to a position where the plug 13 clears the gate 42 in order that the gate may be closed and the apparatus of the invention removed from the position atop the vacuum tank 34.

In order to rotate the screws 43 simultaneously, a chain drive system is provided. A spindle 51 at the upper end of each of the screws 47 passes through the associated bearing 46 and has a sprocket 52 mounted thereon. A chain 53 passes around the sprockets 52 and, through suitable idler sprockets, not shown, passes around a drive sprocket 54. The drive sprocket 54 is positioned in a sub-chamber 56 provided in the wall of the enclosure 32 and is driven by a drive shaft 57 which passes into the sub-chamber 56 through a suitable vacuum seal, not illustrated. The shaft 57 is driven by an electric motor 58.

A hydraulic control system 61 is coupled by suitable hydraulic piping 62 and 63 and flexible hoses 64 and 66 to the upper and lower chambers 24 and 26, respectively. The control system 61 may comprise any suitable arrangement of solenoid operated valves and associated hydraulic circuitry for exhausting the upper chamber 24 and inletting fluid to the lower chamber 26 when the ram is to be raised, and for exhausting the lower chamber and inletting fluid to the upper chamber when the ram is to be lowered. One type of control system is described subsequently in this specification.

As previously mentioned, the invention has particular advantage in connection with continuous casting in vacuum where the particular nature of the vacuum casting process precludes the use of well known expedients for effecting rapid solidification of the ingot. The vacuum tank 34 may completely enclose the unillustrated means for pulling the ingot downwardly through the mold 11, but it is preferable that the tank terminate at the mold. In the latter case, the ingot may be pulled through a suitable vacuum valve, not shown, or may be pulled into a vacuum tank, not shown, specially designed for receiving the ingot, such tank being releasably attachable to the main vacuum tank under the mold 11.

Control over the movement of the ram 18 and hence the position of the plug 13 is provided by an electric control system 67. The electric control system 67 may be of any suitable design to provide signals for operating appropriate valves in the hydraulic control system 61 to cause the piston 23 to move upwardly or downwardly or stop within the housing 22. Suitable circuitry, incorporating such elements as relays and switches for controlling the valves in the hydraulic control system 61, may be easily designed by a person skilled in the art from the description of the operation of the apparatus setout in detail below. Accordingly, details of electric control system 67 will not be described herein.

The upper end of the piston rod 19 is provided with a collar 71 to which an arm 72 is attached extending horizontally therefrom. A rod 73 extends downwardly from the arm 72 into the space adjacent the hydraulic cylinder 21. A bracket 74 extends horizontally outward from the top of the hydraulic cylinder 21 and is provided with an opening therein through which the rod 73 passes, thereby steadying and guiding the rod 73 such that it remains in vertical relation with the piston rod 19 as the piston rod moves vertically upward and downward. The lower end of the rod 73 is provided with an actuator plate 76. The actuator plate thus moves upwardly and downwardly in correlation with the movement of the piston 23.

Upward movement of the ram 18 is limited by providing a suitable electrical signal to the electric control system to operate the appropriate valves in the hydraulic control system 61. The electrical signal for the electric control system 67 is caused by the actuation of an upper limit switch 77 which is supported on a bracket 78 extending downwardly from one of the bearing support brackets 47. The actuator plate 76 on the lower end of the rod 73 engages the switch 77 as the piston 23 approaches the upper end of the hydraulic cylinder. Once the switch 77 is actuated, the switch 77 being connected to the electric control system 67 by suitable means not illustrated, the electric control system provides a suitable signal to the hydraulic control system 61 to stop the movement of the piston by actuating appropriate valves.

In addition to the limit switch 77, the bracket 78 also supports a further limit switch 79. The limit switch 79 is

positioned to be engaged by the actuator plate **76** at a predetermined position in the downward movement of the piston **23**. The predetermined position is selected such that it is just prior to the time the plug **13** engages the molten material at the top of the ingot **12**. As will be explained in greater detail below, the signal provided by actuation of the switch **79**, which is connected to the electric control system **67**, causes the hydraulic control system **61** to operate in a manner which slows the downward movement of the ram **18**. By doing so, movement of the ram **18** downwardly may be initially fast, but may be slower prior to contact in order to avoid splashing of the molten material in the pool when the plug **13** makes contact.

For the purpose of limiting the lower extent of travel of the ram **18**, a pressure sensor, described below, is provided in the hydraulic control system **61** for sensing the pressure in the chamber **24** of the hydraulic cylinder **21**. As will be explained, this pressure sensor provides an appropriate output signal when the pressure in the chamber **24** exceeds a predetermined level which is selected on considerations explained below. The pressure in the chamber **24** rises, as will be explained below, when the plug **13** encounters resistance in its downward movement due to contact with solidifying material at the top of the ingot **12**.

In operating the apparatus of the invention, the ram **18** is lowered until the plug **13** is partially immersed in the center of the molten portion of the ingot **12**, such molten portion being indicated at **81**. The surface **16** of the plug thereby provides a central heat sink surface which solidifies the central portion of the ingot. This is in addition to the annular solidification resulting from the loss of heat into the cooled mold **11**. The result is the formation of a liquid-solid interface **82** having the appearance illustrated. Were it not for heat removal in the central region of the ingot, the liquid-solid interface would form a generally parabolic outline part of which is indicated by the dotted line **83**. The parabolic interface would extend very deeply into the ingot as shown and results in a very slow cooling rate in the central region of the ingot. This slow cooling rate may result in segregation problems, as described above, and may under some extreme conditions become so deep as to require an excessive length in the mold walls in order to prevent the thin-walled partially solidified ingot from expanding or rupturing due to insufficient strength to contain the pressure of the molten metal therein.

In accordance with the invention, the ram **18** is reciprocated in order that the plug **13** is alternately plunged into the central region of the molten top of the ingot and is then withdrawn to allow molten metal to fill the cavity which it leaves. By selecting suitable operating parameters such as the ingot withdrawal rate, the temperature of the molten metal, the time in which the plug **13** is immersed, and the time in which the plug **13** is withdrawn, it is possible to achieve uniform solidification of the central region of the ingot. The thus solidified central region is free of voids and possesses a much finer grain size than in the surrounding annulus. This is due to the hot working which occurs when the cone contracts partially solidified metal as will be explained.

In continuous casting carried out in high vacuum, it is preferred that the top of the ingot be heated (hot topped) by means of an electron beam or beams in order to eliminate the possibility of the formation of pipes or discontinuities in the casting. The beams are directed against the top of the molten material when the plug **13** is not in contact. When the plug is in contact, the beams may be allowed to impinge on part or all of the annular region of the ingot surrounding the plug in order to ensure that molten metal will flow into the cavity left by the plug. If desired, a tubular shield (not shown) may be placed around the plug and lower end of the ram **18** to prevent impingement of the electron beams thereon. In this way, the heat removal characteristics are improved, since the electron beams do not strike the plug or ram directly.

Referring to FIG. **2**, the plug **13** is shown in its inserted position. The molten material in the cavity is spread out in a thin layer (*a*) over the top of the ingot due to the action of the plug (shown exaggerated in thickness for clarity), and a slight rise in the level of the liquid at the mold occurs. This presents little problem, however, since plugs which are immersed several inches in the molten material will cause a rise which is typically less than 1/10 inch.

It may be seen from FIG. **2** that, when the plug **13** is immersed in the molten material **81** at the top of the ingot **12**, heat is removed from the central region **84** by both the plug and the solid ingot. A shrinkage cavity may be produced along a line between the top surface of the solidified ingot and the lower surface of the plug, but the cavity is forced closed and welded shut by the pressure of the plug. A ring (*b*) of molten material also forms between the plug and the mold, extending downwardly a distance which is slightly greater than the lowest level reached by the apex of the plug. Preferably, the plug is forced downwardly to provide a substantial degree of hot working. By doing so, it is also more readily possible to withdraw the plug without having metal adhere to its outer surface and thus produce an undesired buildup on the plug. The conical surface of the plug is large enough and flat enough so that partially solidified metal will not grip the plug and inhibit its withdrawal.

In FIG. **3**, the plug is shown withdrawn and the cavity which it produces is shown empty. A small annular dam (*c*) is formed due to the cooling at the outer periphery of the plug. After a short period of time, electron beams played on the top surface of the ingot, or the heat of the molten metal in the ring (*b*), or the hot additional molten metal being added from the tundish **36**, or all of these cause the annular dam (*c*) to melt. Molten metal then runs into the cavity and fills the cavity as shown in FIG. **1**. The lower portion of the molten pool may be partially solidified as shown in FIG. **1** at (*d*) due to heat transfer into the solidified ingot. The plug is then returned into engagement with the central portion of the molten pool as shown in FIG. **2** again causing solidification of the layer of molten metal between the plug and the solidified ingot. Several sectioned layers are shown in the drawings, exaggerated in thickness for clarity, at **86**. These layers represent the successive layers which are squeezed or spread out and solidify upon each stroke of the ram.

The shape of the plug **13** and in particular the lower surface **16** thereof may be of any suitable form depending upon the particular casting system being used and

the particular material being cast. In the illustrated embodiment, the surface **16** consists of a cone having a 150° included angle. Other forms may comprise a conical surface having a 90° included angle, a 120° included angle, a spherical surface, a flat surface with cylindrical sides, or a waffle iron type surface. The plug may be comprised of copper and may be utilized in its bare form or may be plated with a material such as chromium. Coolant passages, not shown, are provided internally of the plug.

Referring now to FIG. **4**, a circuit diagram of the hydraulic control system **61** may be seen. Included in the system is a four-port valve **87** having ports **88**, **89**, **90**, and **91**. Depending upon the particular operational condition of the valve **87**, the various ports may be coupled to each other as shown by the direction of the arrows within the rectangle. Thus, one condition of the valve connects the port **89** with the port **88**, while another condition of the valve connects the port **89** with the port **90** and connects the port **88** with the port **91**. In addition, the valve may be operated to a neutral or off condition in which all of the ports are blocked. A commercially available valve capable of performing in this manner is known as a four-way directional valve available from Vickers Corporation, Valve No. F3-EG5S4-040C-20. The port **89** is connected through a line **92** to a source **93** of pressurized hydraulic fluid. The port **90** is connected through a check valve **94** to the lower chamber **26** of the hydraulic cylinder **21**. The port **88** is connected directly to the upper chamber **24** of the hydraulic cylinder **21**. A relief valve **96** is coupled across the ports **88** and **90** and a relief valve **97** is coupled across the ports **88** and **91**. The port **91** is connected to an exhaust region **95**.

A second four-port valve **98** is provided in the system and includes four ports **99**, **100**, **101**, and **102**. The valve **98** is smaller than the valve **87** for providing a lower rate of flow through the valve. The valve **98** is capable of operating in the manner indicated by the arrows within the rectangle such that the port **100** may be connected to the port **102**. In addition, the valve is operable to a neutral or off position wherein all ports are closed. The port **102** is coupled to the exhaust region **95** and the port **100** is coupled through a flow regulator valve **103**, and a pressure reducing valve **104** to the source **93** of pressurized hydraulic fluid. The port **99** is coupled to the upper chamber **24** of the hydraulic cylinder **21** and the port **101** is coupled to the lower chamber **26** of the hydraulic cylinder **21**. A suitable valve for the valve **98** is a miniature directional valve sold by Vickers Corporation under Valve No. F3-DIL-2C-20.

In operating the hydraulic system **61**, the electric control system **67** changes the condition of the valves **87** and **98** in the proper order to effect the operating sequence desired below. In order to lower the piston **23** and thus lower the ram **18** (FIG. **1**), the valve **98** is operated to the neutral or off condition and the valve **87** is operated to a condition wherein the port **89** is connected to the port **88**. In this condition, hydraulic fluid from the source **93** flows through the line **92**, through the ports **89** and **88** and into the upper chamber **24** of the hydraulic cylinder. Pressure in the lower chamber **26** of the hydraulic cylinder, caused initially principally by the weight of the piston, ram and plug, is relieved through the relief valve **96** which returns hydraulic fluid into the upper chamber **24**. By using this feedback connection, a higher flow rate is achievable and thereby faster piston operation for a given source pressure is attainable. The check valve **94** prevents fluid from entering the port **90** of the valve **87**.

When the limit switch **79** is struck by the actuator **76** (see FIG. **1**) a signal is provided by the electric control system to operate the valve **87** to the neutral or closed position and to operate the valve **98** to a condition wherein the port **100** is connected to the port **99** and wherein the port **101** is connected to the port **102**. Hydraulic fluid from the source **93** then flows through the regulator valve **103** and the pressure reducing valve **104**, through the ports **100** and **99** into the upper chamber **24**. In this condition, the lower chamber **26** is exhausted through the port **101** and the port **102**. The piston thereby continues to move down at a reduced rate of speed until it encounters resistance due to solidified material. The movement of the piston and the pressure in the upper chamber **24** may be compared in FIG. **5** wherein the displacement curve represents the position of the piston and the pressure curve represents the pressure in the upper chamber as sensed by a pressure sensing device **106** (see FIG. **4**). Rapid movement of the piston downwardly continues along the dotted line to the position d_1. It is then slowed down by the action caused by the limit switch **79** as it moves from position d_1 to the position d_2. All this occurs in the time interval t_o–t_1 and wherein the pressure in the upper chamber is at its minimum level.

Once the plug engages the top of the ingot, and encounters resistance due to partially solidified material, movement of the plug is halted in the position d_2. The pressure in the upper chamber **24** also remains constant as fluid continues to flow into the chamber **24**. This is because, during the displacement of the piston from d_1 to d_2, the piston moves downwardly with the flow of fluid out of the lower chamber **26** and is not forced down by increasing pressure.

When the fluid fills the upper chamber **24**, the pressure begins to increase. At the time t_2 or shortly thereafter, the increased force resulting from the increase in pressure causes hot working in the metal and the plug and piston then begin to move down. This pressure buildup increases and downward piston movement continues in the interval t_2–t_3 until the pressure in the upper chamber **24** exceeds the sensing level of the pressure sensor **106**. When this occurs, the electric control system operates the valve **98** to a neutral or off condition and operates the valve **87** to a condition indicated by the crossed arrows, that is, with the port **89** connected to the port **90** and with the port **88** connected to the port **91**. In this condition, hydraulic fluid under pressure from the source **93** flows through the line **92**, the ports **89** and **90** and the check valve **94** into the lower chamber **26**. At the same time, hydraulic fluid in the upper chamber **24** is exhausted through the ports **88** and **91**. As a result of switching to the exhaust condition, it may be seen that the pressure in the upper chamber **24** at time t_3 begins to drop quickly and that the piston **23** begins to move upwardly from its lowermost position at d_3. Such movement continues until the actuator plate **76** engages the limit switch **77**. At this time, the valve **87** is operated to the originally

described condition, and the valve **98** is operated to the neutral or off condition. Downward movement of the piston then resumes.

Generally speaking, and for most materials, satisfactory results are obtained when the plug is held in contact with the ingot for a time interval in the range of about 3 to 10 seconds, and wherein it is held out of contact with the ingot for a time interval in the range of 2 to 6 seconds. In order to achieve this, the electronic control system incorporates time delay circuitry to provide a desired dwell time after triggering of the upper limit switch **37** or of the pressure sensor **28**. Moreover, in order to achieve freedom from segregation for most materials, the size of the plug and the cooling thereof are chosen so that the heat removal from the central section of the ingot is such that the diameter of the central solidified region formed by the coolant plug is not greater than about **8** inches smaller than the effective diameter of the ingot. This prevents the annular molten pool (**81** in FIG. **2**) from becoming excessively deep whereby slower solidification time would result with consequent segregation problems. Immersion times of less than about **3** seconds may result in the solidification of a thin tightly adhering shell on the plug which proceeds to build up on succeeding immersions. Moreover, sufficient upward force must be provided as to enable the plug to disengage from the ingot after the plunge and dwell. Immersion times greater than about 10 seconds make it extremely difficult to remove the plug from the ingot. Generally speaking, a disengagement time of about 2 to 6 seconds enables molten material to run back into the cavity produced by the plug before the plug is brought back into contact with the ingot.

For most materials the pressure exerted by the plug should exceed about 60 psi. At pressures less than this, there may be a tendency for solidified metal to adhere to the plug as the plug is withdrawn. This occurs because insufficient hot working has been effected to weld the layers immediately adjacent the plug to the lower layers of the solidified central region of the ingot. The minimum required pressure varies depending on the properties of the material, however, and some materials may require a higher pressure. In particular, those materials which have a solidification range of about 50° or more, and those materials which have low thermal conductivity, such as **304** stainless, typically require much higher pressure levels to insure proper ingot formation. There is no theoretical limit to the maximum pressure, but it should not, of course, exceed the loading capabilities of the ingot pulling apparatus.

Use of the invention in connection with Fe26Cr, Fe20Cr, material sold under the trademark WASPALLOY, and 4340 steel, have resulted in ingots wherein longitudinal grains were formed in the annular region surrounding the central region of the ingot and wherein the central region consisted of substantially smaller grains of an equiaxial nature. These smaller grains in the central region of the ingot have a random orientation with respect to those in the annular region where the longer grains are present. Experiments have shown that the presence of segregation problems in ingots cast in accordance with the invention are substantially eliminated, and very dramatic improvement results in connection with large diameter ingots, such as those ingots exceeding about 12 inches effective diameter. By effective diameter, it is meant the diameter of a cylindrical ingot or the distance across the flats of a round corner square ingot.

The dramatic improvement of ingots cast according to the invention in terms of the elimination of segregation problems has been observed in connection with 4340 steel. Ingots cast without central cooling in accordance with the invention have been compared with ingots cast in accordance with the invention and have been found to be of significantly lower ductility. For example, tests of 4340 steel show an improvement of almost 10 percentage points in the percent reduction in area values over vacuum cast ingots in which central cooling was not employed.

It may therefore be seen that the invention provides an improved method and apparatus for continuous casting in which problems of segregation are minimized. The invention has particular advantage in connection with the vacuum casting of large diameter ingots and enables a significant improvement in the casting rates attainable.

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. Apparatus for use in a continuous casting system including a casting mold for continuously casting an ingot of solid cross section and means for pulling the cast ingot downwardly through the mold, said apparatus comprising, a plug having a solid cross section less than the cross section of the casting mold, means for supporting said plug above the casting mold aligned substantially with the longitudinal axis thereof, means for moving said plug reciprocally to repeatedly engage and disengage the central region of the molten pool at the top of the ingot in the casting mold, and means for removing heat from said plug to cool the ingot being cast in the mold in the central region thereof.

2. Apparatus according to claim **1** wherein the lower end of said plug has a conical surface.

3. Apparatus according to claim **1** wherein said heat removing means comprise means for circulating a fluid coolant in contact with said plug.

4. Apparatus according to claim **1** wherein said moving means include a reciprocable hydraulic cylinder, means for sensing a rise in pressure in the upper part of said cylinder to a predetermined level in response to resistance to movement of said plug exerted by the ingot, and means responsive to the sensing of the predetermined pressure for stopping said plug and for reversing the action of said cylinder after a predetermined time delay.

5. Apparatus according to claim **4** wherein said moving means include a limit switch positioned to be actuated upon a rise of said plug to a predetermined upper position, and means responsive to the actuation of said limit switch for stopping said plug and for reversing the action of said cylinder after a predetermined time delay.

* * * * *