METHOD FOR CONTINUOUS CASTING

A method and apparatus are 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.

8 Claims, 5 Drawing Figures

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ABSTRACT

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METHOD FOR CONTINUOUS CASTING

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 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 or 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 interdendritic 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 arm, 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 introduced 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 than 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 undesirable and is evidenced by the added molten material. Once the central post is undercut, the top of the solidified post will pull away with the
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 two inches from the inner surface of the mold. The plug is left in contact with the ingot for 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 just sufficient to allow a thin layer of new molten metal to run into the contacted region. Generally speaking, the thinner the laminae 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 one-half 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 metal 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 very rapid and the freezing zone very small. In other words, there is accomplished high heat removal from a relatively small volume of molten metal.

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, 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 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. 75
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 molten metal 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 set out 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 becomes 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 metal 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 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 as 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. Thus, the 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 one-tenth of an 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, the 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 lower than the lowest level reached by the apex of the plug. Preferably, the plug should be 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.
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so that partially solidified metal will not grip the plug and in-
hhibit 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 it 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 sectional 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 other 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 85, 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 0F3-EGS54-040C-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 port 101 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 connected 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 0F3-12C-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 condi-
tion 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 26 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 achieved and thereby increases the position 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 open 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 downward at a reduced rate of speed until it encounters resistance due to solidified metal. 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 downward continues almost to the dotted line to the position d1. It is then slowed down by the action caused by the limit switch 79 as it moves from position d1 to the position d2. All this occurs in the time interval t1-t2 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 d2. 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 d1 to d2, the piston moves downward 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 t1 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 t2-t3. As 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 t3 begins to drop quickly and that the piston 23 begins to move upwardly from its lowestmost position at d2. 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 p.s.i. 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 ensure 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 WAPALLOY, 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.

What is claimed is:
1. A method for continuously casting an ingot, comprising, pouring molten metal into a cooled continuous casting mold and pulling the cast ingot downwardly through the mold, contacting the molten pool at the top of the ingot at the central region thereof with a cooled plug to remove heat from the central region and to cause a substantial amount of the metal under the plug to solidify, removing the plug from contact with the ingot to allow molten metal to flow into the region of the ingot which was under the plug, and repeating the contacting and removing steps while the ingot is cast.
2. A method according to claim 1 wherein the ingot is contacted by the plug with a force to provide hot work in the central region of the ingot sufficient to prevent adherence of metal to the plug when it is withdrawn.
3. A method according to claim 1 wherein the plug is brought into contact with the ingot at intervals sufficiently frequent as to maintain the layer solidified on each contact at less than about one-half inch.
4. A method according to claim 1 wherein 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 about 2 to 6 seconds.
5. A method for continuously casting an ingot, comprising, pouring molten metal into a cooled continuous casting mold and pulling the cast ingot downwardly through the mold, extracting heat from the central region of the molten pool at the top of the ingot to cause a substantial amount of the metal thereat to solidify, and simultaneously applying pressure to such region by means of a cooled plug to produce a substantial degree of hot work in such region.
6. A method according to claim 5 wherein the pressure exerted on the central region to provide hot working is sufficient to weld the most recently solidified material to that material immediately below it.
7. A method according to claim 5 wherein the pressure exerted on the central region of the ingot to provide hot working exceeds about 60 psi.
8. A method according to claim 5 including the step of adding heat to the top surface of the ingot by means of at least one electron beam.