Oct. 3, 1967 R. C. BUEHL ETAL 3,344,840

METHODS AND APPARATUS FOR PRODUCING METAL INGOTS

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FIG. 1.

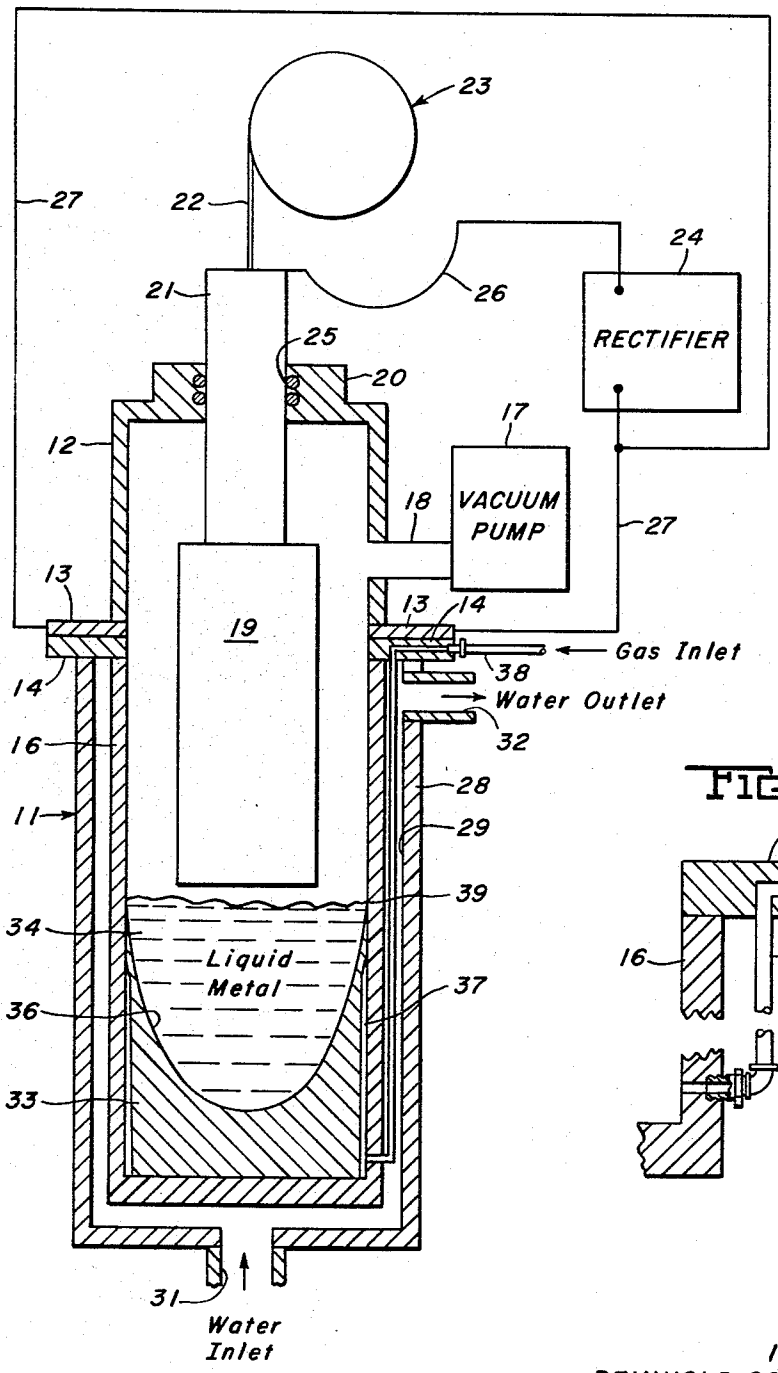


FIG. 2.

INVENTORS.
REINHOLD SCHEMPP and
RUSSELL C. BUEHL
By John R Regan
Attorney

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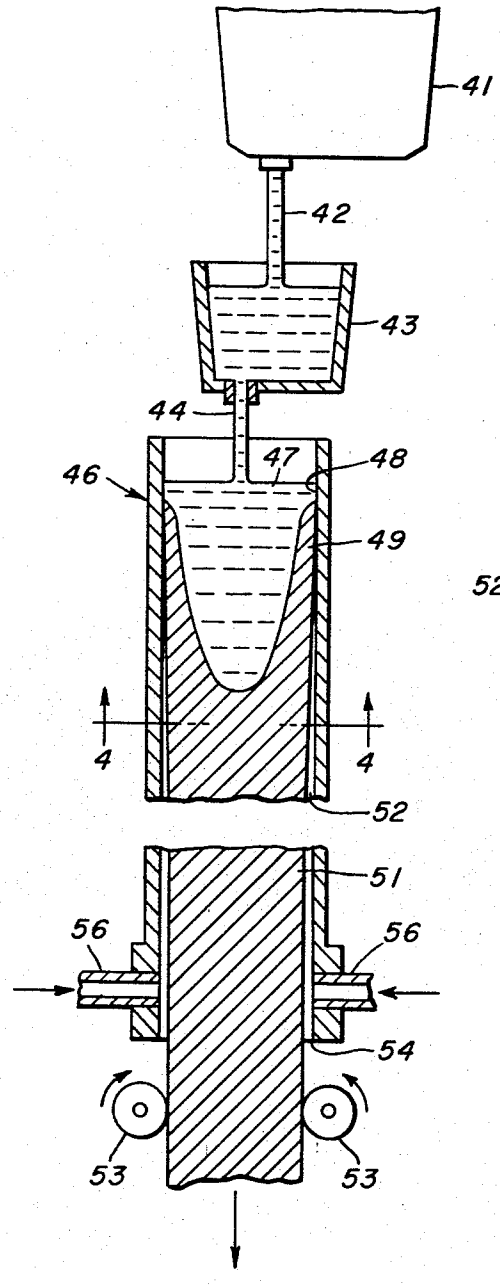


FIG. 3.

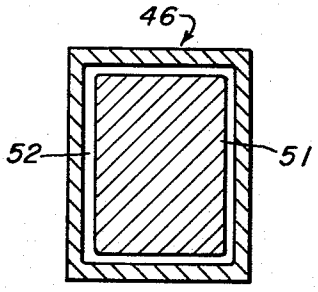


FIG. 4.

INVENTORS.
REINHOLD SCHEMPP and
RUSSELL C. BUEHL

By John R. Regan
Attorney

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METHODS AND APPARATUS FOR PRODUCING METAL INGOTS

Russell C. Buehl, Beaver, Pa., and Reinhold Schempp, Clay, N.Y., assignors to Crucible Steel Company of America, Pittsburgh, Pa., a corporation of New Jersey

Filed July 1, 1966, Ser. No. 563,636
6 Claims. (Cl. 164—122)

This application is a continuation-in-part of our application Ser. No. 289,687, filed June 21, 1963, and now abandoned.

This invention relates to improved methods and apparatus for the production of metal ingots and, in particular, to improved methods and means for producing metal ingots of a high degree of homogeneity and consequently enhanced physical properties.

The invention has special application to the production of metal ingots by the vacuum arc remelting process.

The consumable electrode vacuum arc remelt process is used for the production of high quality metals for special applications. The process eliminates the center porosity and the poor center transverse mechanical properties normally associated with ingots made by pouring metal from a ladle into a mold. However, various types of inhomogeneity occur during the solidification of vacuum arc remelted ingots of many compositions. Such inhomogeneities are usually more pronounced in large ingots than in small ingots. Inhomogeneity in vacuum arc remelted ingots can usually be minimized by conducting the melting operation at as low a current as is practical from other considerations. However, melting at low current gives a low melting rate and therefore a low output per furnace and also a rough ingot surface with poor processing yield.

Consequently, methods and means for the rapid production of large vacuum arc remelted ingots are of special desirability and, indeed, economic necessity in the metallurgical arts.

Continuous casting affords a high speed, low cost method of producing ingots, slabs, billets and other mill product forms of steel and other metals. Such processes, and equipment for performing the same, involve the teeming of molten metal into a cooled mold, e.g., of copper, continuously solidifying the metal therein, and withdrawing an elongated cast article from an open lower end of the mold. Highest continuous casting speeds are desirable for maximum production volume. Permissible casting speed is dependant, among other factors, upon rate of heat extraction from the metal being cast, through the mold wall, and to the mold cooling medium.

Accordingly, it is an object of this invention to provide methods and apparatus for enhancing the homogeneity of metal ingots.

It is a particular object of the invention to provide methods and means for improving the homogeneity and physical characteristics of metals and alloys melted by the vacuum arc remelting technique.

It is a further object of the invention to provide methods and means for increasing the melting rate of consumable electrodes in the vacuum arc melting process, while simultaneously enhancing the properties of ingots melted thereby.

It is yet another object of the invention to provide methods and means for enhancing the rate of solidification and the casting speed of continuously cast ingots.

The foregoing and other objects of this invention are embodied in the method wherein a gas, preferably a low molecular-weight gas, as hydrogen or helium, is introduced into the shrinkage cavity formed between the cooling ingot and the mold wall upon solidification of the melted metal and contraction thereof so as to form a small but discrete space therebetween.

In a further aspect of the invention, means are provided, inclusive of a mold, having an aperture therein interconnecting with the aforesaid shrinkage cavity and means to supply thereto a low molecular weight gas.

The foregoing and other objects of the invention will become more readily apparent by an inspection of the following description and drawings, wherein:

FIG. 1 is a schematic side elevation, partly in cross-section, of a vacuum arc remelting furnace, incorporating the features of the invention;

FIG. 2 is an elevational view, partly in cross-section, of a portion of the vacuum arc melting furnace apparatus, illustrative of means for introducing a cooling gas into the furnace mold and about the solidifying ingot;

FIG. 3 is a schematic elevational view, partially in cross-section, of a continuous casting apparatus, incorporating the gas-cooling features of the invention, and

FIG. 4 is a cross-sectional plan view, taken along line 4—4 of FIG. 3, and showing the generally annular shrinkage space between mold wall and solidified ingot into which space a cooling gas is introduced in accordance with the invention.

Referring now to the drawings, and particularly to FIG. 1 thereof, the numeral **11** refers generally to a vacuum melting furnace comprising a cylindical, metallic furnace shell or housing **12**, to a lower extremity of which is attached, by suitable means, as flanges **13** and **14**, a water-cooled, cylindrical mold **16** which is generally constructed of copper because of the high heat conductivity of that metal, but which may, with advantage, be constructed of mild carbon steel in accordance with the teachings of co-pending application Ser. No. 219,223 of Russell C. Buehl. A vacuum pump **17** is provided with an exhaust line **18** which is interconnected with the interior of the furnace shell **12** for exhausting gases from the furnace **11**. An electrode is suspended concentrically within the furnace **11** and is supported therein by an electrode support **21**. Mounted atop the furnace shell **12** is a suitable gasket-bearing means **20** provided with a centrally located aperture **25** for passage therethrough of the electrode support **21**, and adapted to seal the interior of the furnace against ingress or egress of gases during movement of the electrode support. The latter is connected to suitable means for raising and lowering the electrode within the furnace, for example, by means of a cable **22** and hoist pulley **23**. Electrical power is supplied by suitable means such as a rectifier **24** which is connected to the electrode support **21** by means of a flexible, electrical power cable **26** and to the mold **16** by means of bus bars **27**. A jacket **28** is provided concentrically of the mold **16** and spaced therefrom to provide an annular space **29** for passage therethrough of a cooling fluid from a fluid inlet **31** to a fluid outlet **32**.

During operation of the usual vacuum arc furnace the interior thereof is evacuated, by means of pump **17**, to a suitably low pressure whereupon an arc is struck between the lower extermity of the electrode **19** and a mass of solidified starting metal, as **33**, in the bottom of the mold **16**. The electrode **19** is constructed of the metal to be melted and, when the arc is produced, the metal electrode melts and drops of molten metal fall from the lower extremity of the electrode into the mold to produce a pool **34** of molten metal which is contained within a cup-shaped depression **36** within the solidified metal **33**. As melting of the electrode **19** progresses during continued operation of the furnace, the zone of solidification between the liquid metal **34** and the solidified metal **33** moves upwardly within the mold **16**.

The gradual movement of the solidification zone from the bottom toward the top of the solidified ingot, as melting progresses, substantially eliminates the center porosity which is usually observed in poured ingots. Such vacuum

arc melting processes and apparatus tend substantially more toward elimination of undesirable non-metallic inclusions than do prior art processes and apparatus involving the pouring of the molten metal into a mold. For example, hydrides and some nitrides decompose at the high temperatures and low pressures existing in vacuum arc furnaces and the resulting gases are pumped from the furnace. Many oxides react with carbon in the metal to yield carbon monoxide which is also evacuated from the furnace. Some, but not all, unreactive oxides are eliminated, in the vacuum arc melting furnace, by floating to the surface of the molten metal.

Investigations by the inventors have established the shape and location of the liquid pool **34** at five-minute intervals during a typical melting cycle in accordance with usual practice. This work showed that the pool depth often exceeded the 12-inch diameter of the crucible **16**. The measured pool depth, when melting steels at the currents normally employed, e.g., about 400 to 600 amperes per inch of mold diameter, was much deeper than the shallow pool normally indicated in prior art descriptions of the process. The movement of the solidification zone during a five-minute period was measured as the distance between successive pool lines. From such measurements, the rate of solidification was determined for all portions of the ingot and was found to be extremely low in some portions of vacuum arc remelted ingots made in the usual manner of the prior art, as above described.

The shape of the pool lines indicated that improved heat transfer between the ingot and the water-cooled mold **16**, especially in the lower portion of the ingot, would decrease the pool depth and increase considerably the magnitude and uniformity of the solidification rate. Accordingly, methods and means were sought for accomplishing this objective.

As soon as a thin skin of metal near the top of an ingot cools appreciably below the solidification temperature, the ingot shrinks away from the water-cooled mold **16**, thereby forming an annular shrinkage space, denoted by the numeral **37** in FIG. 1. This space is generally quite small, the distance from mold wall to ingot surface rarely exceeding one-sixteenth to one-eighth inch (depending upon ingot size and composition) and varies, of course, from top to bottom of the ingot-mold system. Under the condition of prior art practice, the space **37** between the ingot and the mold **16** is probably filled with a gaseous mixture consisting largely of nitrogen, hydrogen and/or carbon monoxide at a pressure not much above that in the furnace wherein, under current practice, pressures from about 1 to about 50 microns are generally employed. Calculations indicate that, under such conditions, nearly all of the heat transfer from the ingot to the mold is by means of thermal radiation and that gas conduction and convection contribute very little to the heat transfer. The heat transferred by radiation is given by the Stephen-Boltzman law:

$$\text{Heat transfer} = CT^4$$

wherein:

C is a constant, and
T is the absolute temperature.

The rate, per unit area, of radiative heat transfer from the ingot to the mold is high for the upper portion of the ingot-mold system, wherein the temperature differential between the ingot and the water-cooled mold **16** is great, due to the high temperature of the just-solidified ingot. However, the radiative heat transfer rate is relatively much less in the lower portions of the ingot-mold system wherein the temperature differential between ingot and mold is lower due to the lesser temperatures of the lower portions of the ingot. Thus, normal cooling processes are productive of wide variations in thermal gradients throughout the ingot, both radially and from top to bottom thereof, thereby creating undesirable non-uniformity in the solidified metal structure.

A principal cause of difficulty encountered in the production of homogeneous ingots by vacuum arc melting, as above described, is the absence of uniform, maximum temperature differential or gradient between the interior portions of the ingot and its surface. Limitation, as aforesaid, in prior art methods and means, of heat transfer, from ingot to mold, to the radiation mechanism, is productive of a temperature gradient, from inside the ingot to its surface, which is considerably less than if more efficient heat transfer mechanisms were operative to cause the ingot surfaces uniformly to approach that of the walls of the water-cooled mold **16**. Such low, non-uniform temperature gradient leads to slow and erratic solidification rates in ingots and is a major cause of ingot inhomogeneities. But, if the ingot surface temperature were decreased, then heat transfer by radiation, would, as shown above, be drastically diminished. The problem, then, is to substitute, for the relatively inefficient radiative heat transfer mechanism operative in prior art methods and means of vacuum arm melting, a more efficient mechanism which will avoid the aforementioned disadvantageous results of the prior art.

In accordance with this invention, there is introduced into the shrinkage space **37**, during melting and solidification of the ingot, a gas, preferably one of low density, e.g., having a molecular weight below about **28**, in sufficient quantity to raise the partial pressure of such gas in the space **37** to a value sufficiently high to insure effective heat transfer thereby, from the ingot to the mold wall, by the gaseous conduction mechanism. A desirable minimum partial pressure of the contemplated gases has been found to be about 8–10 mm. Hg in order to obtain highest heat transfer. Lower gas pressures may be used while still obtaining significant benefits. Non-oxidizing gases are preferred in order to avoid oxidation or contamination of the hot ingot, although, for non-reactive metals, other low density gases, as water vapor, may be utilized. In any event, the gas used should be one which is substantially non-reactive with the metal being melted or cast. Preferred gases are hydrogen and helium, both by reason of their non-oxidizing character and, most importantly, because of their very low density and hence the high rate of conductive heat transfer obtainable thereby.

It has been found that such gases, when introduced, as through one or more inlet pipes **38** (FIGS. 1 and 2) adjacent the bottom of the mold **16**, into the shrinkage space **37**, are readily maintained, at very small gas flow rates, at pressures, for example, upwardly of 10 mm. Hg without materially affecting the desired, low operating pressure, as aforesaid, in the furnace. In order not to interfere with the normal operations of assembly and disassembly of the furnace apparatus, the line **38** may conveniently enter through the mold flange **14** (FIG. 2), extend thence through the cooling space between mold **16** and water jacket **28**, and extend through the wall of the mold **16**, as illustrated, adjacent the bottom of the mold. Thus, when using means as illustrated in FIGS. 1 and 2, wherein a pressure tap line, with a bellows-type pressure gage inserted therein, was provided in the wall of the mold **16**, several inches above the gas inlet entrance apertures, and wherein the light gases hydrogen and helium were introduced, gas pressures of from 9 to 26 mm. Hg were readily maintained, in 12- and 16-inch diameter molds, with gas flow rates between 0.08 and 0.15 cubic feet per minute. Under such conditions, there was no appreciable increase in furnace operating pressures in the above-mentioned range (1–50 microns).

It is believed that such results are obtainable by reason of a sealing action exerted between the ingot and the mold wall by an annulus of liquid metal, as at **39** in FIG. 1, where as yet unsolidified metal in the pool **34** contacts the mold wall. Such seal effectively precludes escape of the gases introduced into space **37** into the evacuated space above the pool surface. It was also found that if substan-

tially greater gas pressures, i.e., over about 30 mm. Hg, were used, the gas pressure became sufficiently great to cause the gas to overcome the resistance offered by the liquid seal and to bubble through the molten metal with little or no consequent increase in gas pressure within the space **37**.

Utilizing the aforementioned low density gases, within the pressure ranges as aforesaid, resulted in a drastically enhanced rate of heat transfer from the ingot to the mold. This is a surprising and unexpected result, for the prior art has considered only a metal-metal conductive transfer mechanism from ingot to mold wall to be controlling upon cooing rate, and has, consequently, heretofore concentrated attention upon enhancement of such mechanism, as by adoption of molds constructed of materials having highest useful heat conductivities, e.g., copper. In contradistinction, we have now found that highest rates of heat transfer can be obtained by the aforesaid method and means, utilizing heat conduction of high conductivity, i.e., low density, gases in the shrinkage space between ingot and mold wall. In order to achieve highest heat transfer rates, it is necessary to utilize a critically limited minimum gas pressure, as aforesaid, which, it is believed, is required in order to achieve most effective conductive heat transfer from ingot to mold wall. Except at very high ingot surface temperatures, and within the herein contemplated pressure range, gas conduction is the controlling mode of heat transfer, the heat transfer by radiation being relatively much lower. As shown above, it becomes impossible, in the contemplated vacuum furnace system, to achieve gas pressures substantially higher than a maximum value of about 20–30 mm. Hg. Moreover, at pressures above the latter values, there is no significant improvement in the important and desirable effects of conductive gas heat transfer.

Utilization of the methods and means of the invention as above described, is productive of drastic and unexpected improvement in the homogeneity of vacuum arc melted ingots. Thus, enhancement of heat transfer, by the methods and means of the invention, between the ingot and the mold wall, substantially and uniformly lowers the ingot surface temperature, with consequent increase of uniform temperature gradients throughout the ingot, thereby resulting in greater homogeneity of the solidified metal. The enhanced heat transfer rate produced by use of the inventive concepts also decreases the depth of the molten pool at the top of the solidifying ingot, which is also conducive to a superior ingot structure.

Comparative tests were conducted wherein the results of ingot production both with and without the use of the invention were evaluated. Exemplary of such tests, a 1014 pound ingot of AISI 52100 steel was vacuum arc remelted, from an eight-inch diameter, round-cornered square consumable electrode, into a 12-inch diameter copper mold, using an arc current of 6200–6500 amperes, a furnace pressure of about 9 microns, and a melting rate of 7.8 pounds per minute as determined from the rate of electrode movement which, in turn, was dependant upon the rate of melting of the electrode obtainable under the prevailing process conditions. Helium was introduced, at a rate of 0.1 cubic foot per minute, into a bottom corner of the shrinkage space and, at a position 5 inches above the bottom of the mold, the pressure in the shrinkage space was between 8 and 18 mm. Hg. The ingot thus melted was forged to billet form and then sectioned near the bottom end. A transverse disc thus obtained was then polished and etched to ascertain the metallographic structure of the metal. The resulting billet was of an exceptionally homogeneous structure, with no observable inhomogeneities.

A further billet, of the same grade of steel, was prepared, utilizing the same procedure and apparatus as above described, except that no gas was introduced into the shrinkage space. In this instance, the furnace pressure was about 5 microns and the calculated melting rate was 5.3 pounds per minute. The product of the last-described, prior art practice, exhibited the typical, gross inhomogeneities generally associated with vacuum arc remelting.

The compositions of the steels used in the above-described tests are given in the following Table I, from which it will be observed that the steel compositions are in every sense comparable.

TABLE I

Element	Steel	
	S-98703B1 (FIG. 2)	S98314B (FIG. 3)
Carbon	1.04	1.04
Manganese	0.380	0.42
Phosphorus	0.008	0.012
Sulfur	0.008	0.010
Silicon	0.29	0.32
Chromium	1.47	1.48

The unusual and unexpected benefits of the invention, as illustrated by FIGS. 3 and 4, are, as aforesaid, believed attributable to the enhanced heat transfer rate and greater, more uniform ingot temperature gradients resulting from gaseous conduction of the low density gases in the shrinkage space between the ingot and the mold wall. These effects of such gases, present in the above-mentioned pressure range, has not heretofore been recognized by the prior art. The beneficial effect of the especially contemplated, particular class of gases, i.e., low density gases, as, for example, hydrogen, helium or water vapor (the latter material only in the case of melting non-reactive metals), is believed due to their low molecular weight and, hence, to the relatively high molecular velocity and the small disturbance of the velocity vector of a molecule effected by collisions thereof with similar molecules in travelling a given distance under the influence of a temperature gradient. Consequently, such low molecular weight gases are more efficient conductors of heat than are gases of heavier molecular weight, as nitrogen, argon, etc., wherein molecular velocity, under the same thermal energy gradient, is smaller, and wherein velocity vectors and hence preclude efficient conductive thermal energy transfer. The utility of the low molecular weight gases is independent of their specific heat capacities. This is true because the principles of the invention contemplate an essentially static system. That is, the mass flow of gas to the shrinkage space **37** is only sufficient to maintain the required pressure within that space and to make up for the relatively slight quantities of gas which escape past the liquid seal adjacent the pool surface periphery and which are thereby removed by the furnace vacuum system. There is thus essentially no gross convective gas movement or sweep past the hot ingot surface. Thus, due to the low mass flow rate of the low density gas to the shrinkage space **37**, the quantity of heat energy removed from the ingot as heat content in the exiting low density gas is extremely small, for example, on the order of 1.0 kg.-calorie per minute (hydrogen introduced at 0.1 cubic foot per minute, average gas temperature 1500° C.), thus constituting less than 0.1% of the electrical energy input to the furnace for melting under usual conditions with equipment as exemplified hereinabove. The invention does not, accordingly, contemplate or utilize substantial absorption of heat energy from the ingot by a moving gas stream which is then removed from the system. The latter procedures are known to the prior art, for example, as taught in Tessmann U.S. Patent No. 2,837,791, relating to continuous casting and the absorption and removal of thermal energy by a flowing stream of high heat capacity, high molecular weight gases, or as described in Jordan U.S. Patent No. 2,711,955, relating to the provision of relatively high pressure gases in the shrinkage cavity of a continuous ingotting process to provide a self-supporting skin of solidified metal about the ingot periphery.

The principles of the invention are not limited as to the types of materials which may be improved by use of the inventive features, and may, with highly beneficial results, be used in the production of bearing steels, low alloy structural steels, tool steels, superalloys, refractory metals, as tungsten, tantalum, columbium, vanadium, molybdenum, titanium, etc., and alloys thereof—indeed, any metal which is improved in respect of contemplated end uses by enhancement of homogeneity.

Moreover, the invention is not limited to use in vacuum arc melting, but may also be applied with advantage in other melting practices, such as those utilizing continuous casting apparatus and methods. Thus, FIG. 3 is illustrative of a continuous casting facility comprising a ladle **41** for transport of molten metal, and from which the metal is teemed, as in form of the stream **42**, into a tundish **43**. From tundish **43**, the metal is teemed, as at **44**, into a continuous casting mold, denoted generally by the numeral **46**. The mold comprises elongated, vertically extending walls of a highly heat conductive metal as copper, which is externally cooled, as by spray or a circulating stream of water.

The molten metal, upon introduction into the mold **46**, forms a pool **47** extending laterally to the mold walls at the top of the pool and forming therewith an annular seal **48**. A slight distance below the pool surface, the metal begins to freeze, forming a skin **49** of solid metal about the pool **47**, and increasing in thickness as it extends downwardly into the mold, until, finally, a solid ingot body **51** is formed.

As the metal solidifies, it shrinks away from the walls of mold **46**, and forms therewith an annular shrinkage cavity **52**. Thermal energy is, of course, extracted continuously from the metal, liquid and solid, as it progresses through the mold, drawn therethrough by suitable means, as rollers **53**. The speed with which the metal may be cast is dependent, to a large extent, upon the rate at which heat is extracted from the metal.

Normally, in accordance with prior art practices, the shrinkage space **52**, being open at a lower end **54** of the mold **46**, is filled with air and the rate of heat transfer across the space **52**, from ingot to mold, is a factor of the conductivity afforded by the air in space **52**.

As hereinabove set forth, lower density gases, e.g., those having a molecular weight under **28**, for example, hydrogen, helium or water vapor, provide more efficient heat conductors, under the essentially static conditions existing in the space **52**, than heavier gases, as air, argon, nitrogen, etc. accordingly, the invention contemplates methods and means for introducing into the shrinkage cavity **52** such low density gases as above described. For example, the mold **46** may be provided, adjacent the lower end **54** thereof, with one or more pipes **56**, through which such low density gases are fed into space **52**. These gases, being lighter than air, rise in the space **52** to fill it and are effectively prevented from escaping from the top of the mold by the liquid metal seal **48**, so long as the gas pressure does not exceed the atmospheric plus liquid metal head pressure so as to disrupt the seal **48**. The light gases in space **52** diffuse only slowly from the open end **54** of the mold, so that only enough gas is fed to space **52** to replace such losses.

Although, as above described, prior art continuous casting has utilized high molecular weight gases, at high velocities, in the shrinkage cavity of continuous casting molds for the purpose of supporting the thin, solidified peripheral skin of the cast product, the art has previously been unaware of the great advantages of utilizing a low velocity or static, low density gas to increase heat removal conductivity from the continuously cast ingot and thereby to increase the possible casting rate. The invention has the added advantage, in such applications, of simultaneously providing, by the use of inert or non-oxidizing gases, as helium or hydrogen, a protective atmosphere to insure high surface quality of the continuously cast product.

The foregoing description and specific examples and embodiments of the invention are merely illustrative of the principles thereof and it is to be understood that various additions and modifications may be made by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In a vacuum arc melting process, a method of enhancing the rate of melting of a metallic consumable electrode and of enhancing the rate of solidification and the homogeneity of a metal ingot produced thereby, in a mold having fixed sides and bottom, comprising arc melting the electrode into a metal mold, cooling the mold to solidify an outer skin about the molten metal and to form a solid metal ingot below the solidified skin whereby the solidified metal shrinks away from the mold wall to form an annular shrinkage space therewith, retaining a seal of molten metal between the mold and the molten metal above the solidified outer skin, introducing into the shrinkage space below the seal at least one gas substantially non-reactive with the metal, and maintaining the gas pressure in said space at a value less than that sufficient to rupture the molten metal seal and substantially static within said cooling zone, thereby maintaining the gas below the seal and within the shrinkage passage.

2. A method in accordance with claim **1**, wherein the gas is selected from the group consisting of hydrogen, helium and water vapor.

3. A method in accordance with claim **1**, wherein the gas is hydrogen.

4. A method in accordance with claim **1**, wherein the gas is helium.

5. A method in accordance with claim **1**, wherein the gases are maintained in said space at a total pressure of at least about 8 mm. Hg.

6. A method in accordance with claim **1**, wherein each of the gases has a molecular weight below 28.

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J. SPENCER OVERHOLSER, *Primary Examiner.*

V. K. RISING, *Assistant Examiner.*