VACUUM CASTING

Filed June 26, 1962 3 Sheets-Sheet 1

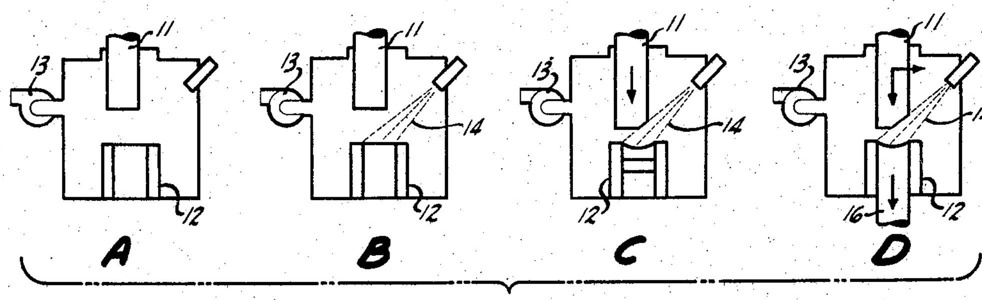

FIG-1

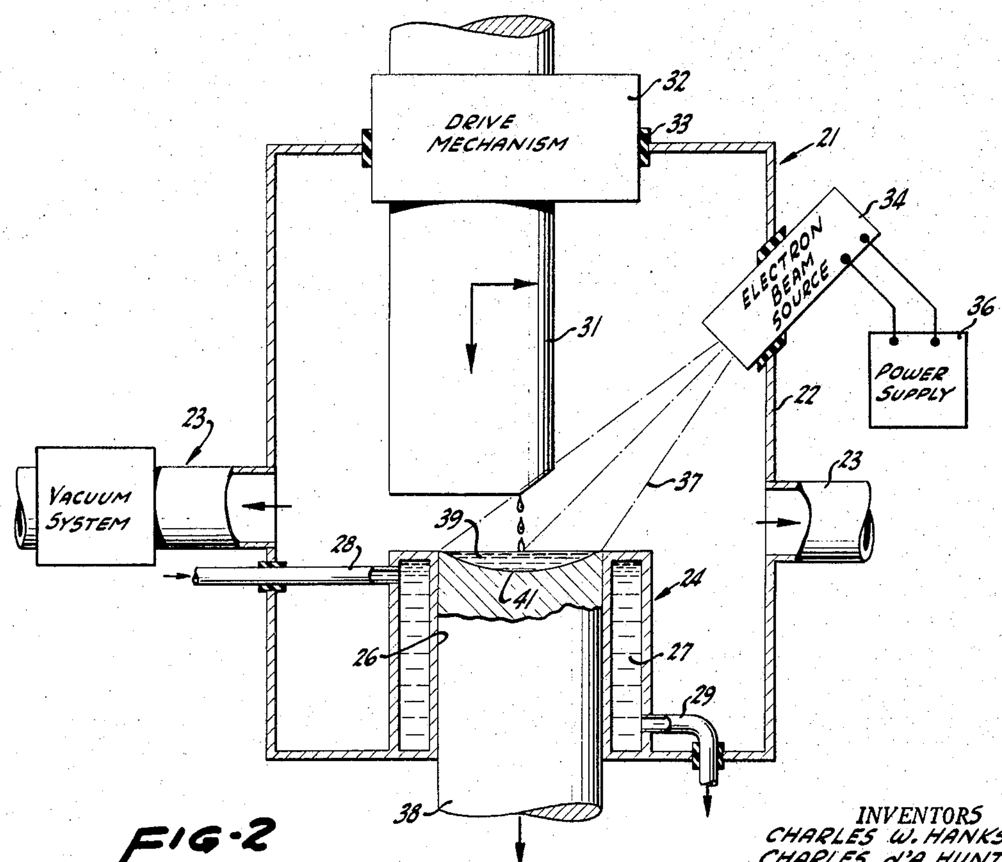

FIG-2

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VACUUM CASTING

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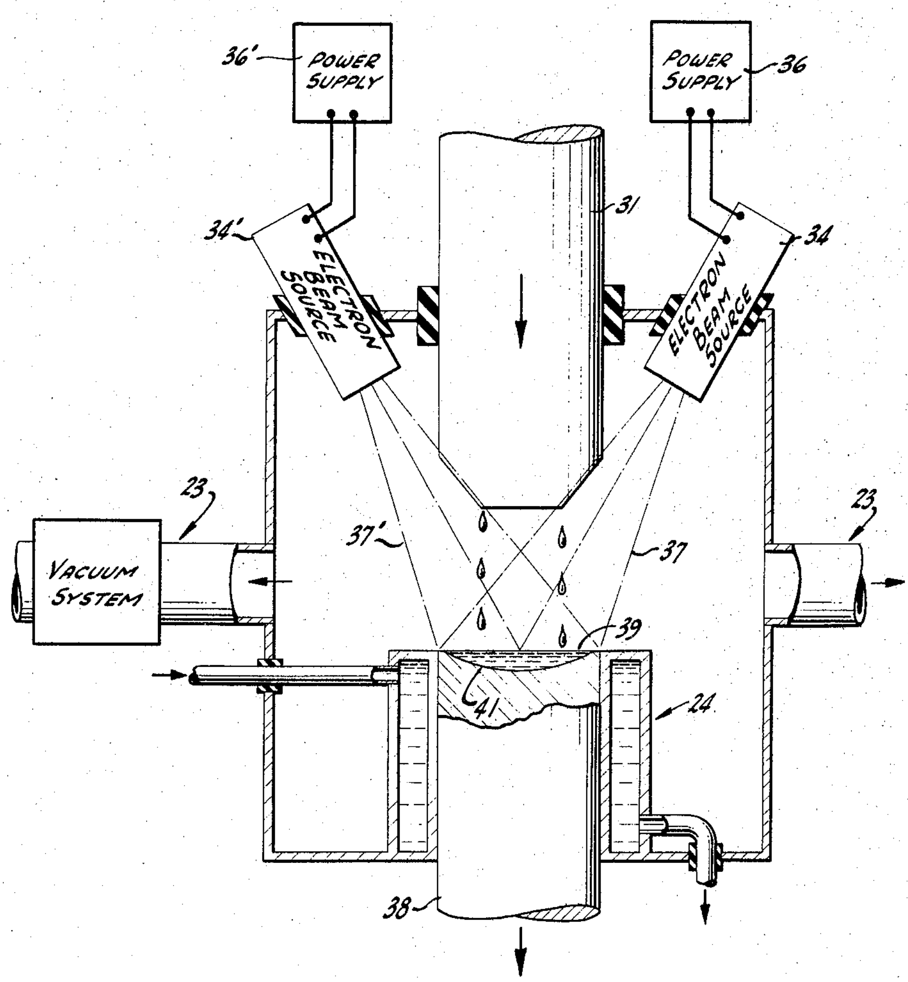

FIG. 3

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VACUUM CASTING

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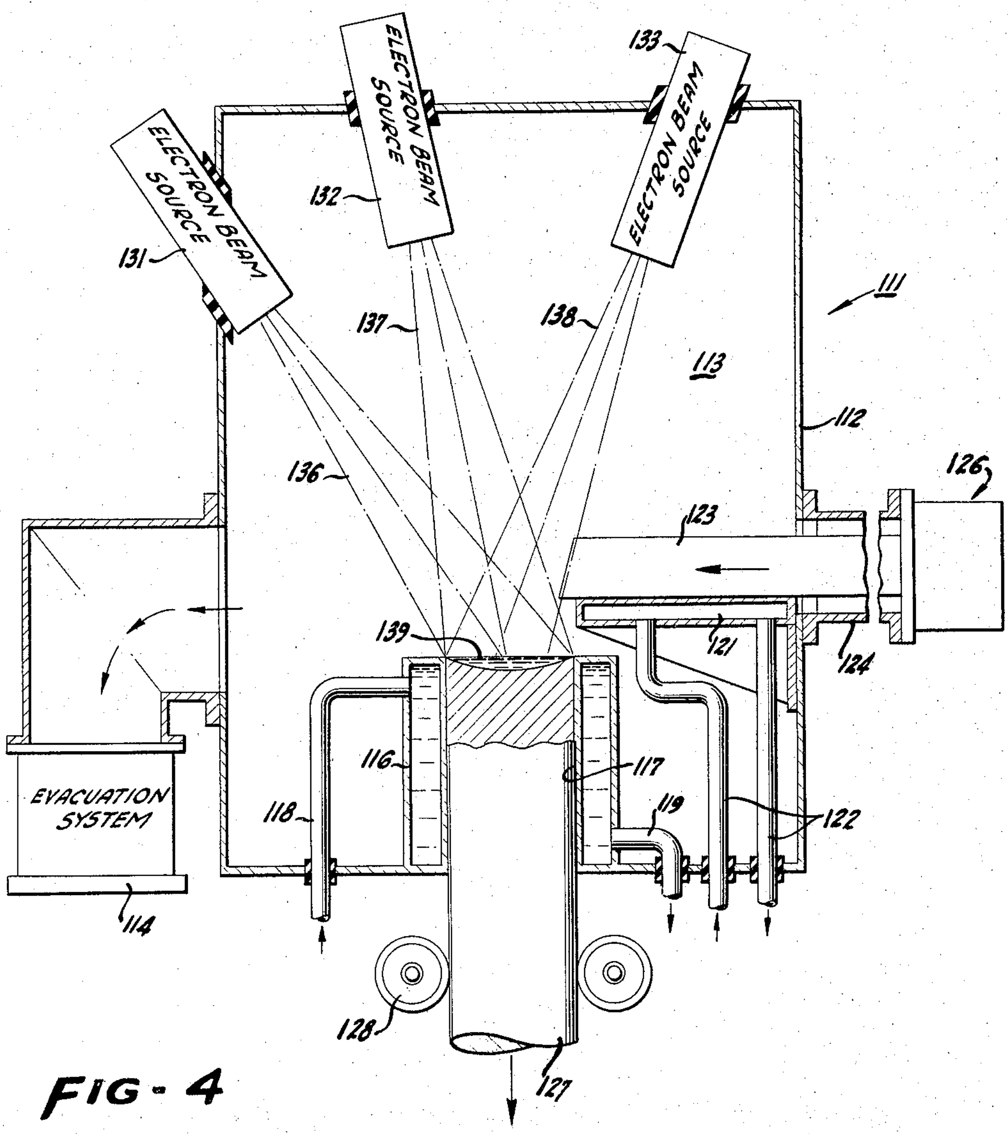

FIG-4

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3,237,254

VACUUM CASTING

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6 Claims. (Cl. 22—200.1)

This application is a continuation-in-part of our co-pending applications Serial No. 810,399 filed May 1, 1959, and Serial No. 813,270 filed May 14, 1959, now abandoned.

The present invention relates to the art of metal casting and purification and more particularly to improved method and means for electron beam casting of materials in vacuum.

In the casting of various "difficult" metals, such as refractory metals, there have long been employed electric discharge techniques wherein arc heating is commonly utilized. Although these techniques are highly useful, they suffer from various limitations including that of ambient gaseous atmospheres, very high current power supply requirements, control difficulties and explosive hazards. Alternative approaches in this field have in the past been generally directed to laboratory apparatus inherently limited to very small scale operations. For example, the common laboratory evaporator may employ an electron beam focused upon a fine wire fed into a crucible to liquify the end of the wire; however, attempts to scale-up such apparatus to production level are unsatisfactory.

Of particular importance in the casting of metals is the resultant internal structure of the cast material, and a substantial advantage results from the removal of gaseous constituents. Thus, deoxidization has long been recognized as beneficial, and likewise the removal of nitrogen and carbon, as carbon monoxide, is quite desirable in many instances, particularly as regards refractory metal. The foregoing will be seen to suggest vacuum processing for maximum devolatilization and, contrary to conventional arc discharge system, the present inventio employs a high vacuum to thereby realize results hitherto unobtainable.

In the furtherance of devolatilization actions it is desirable to provide a control over the heat applied to the material and also over the time during which a material is maintained at an elevated temperature, as for example, in the superheat range. To accomplish this it is necessary not only to melt the material for casting, but also to further controllably heat the liquified melt, and here again conventional techniques fall far short of fulfilling the requirements. Commonly, arc discharge casting, for example, provides very little control over the relative rate of melting and subsequent melt heating. In fact, metallurgical production facilities seldom even consider the fine points of material control herein contemplated. As an example of the foregoing, there have been cast in quantity by the present invention refractory materials of such high purity that they are quite ductile and easily fabricated, in marked distinction to the commonly recognized characteristics of such materials. Additionally, iron, nickel, and cobalt base alloys cast in accordance with this invention have been found to have no observable grain boundary deposits, non-metallic inclusions or differences in transverse and longitudinal properties of forged billets so as to thereby materially enhance their applicability and in fact to endow material so treated with capabilities far beyond those previously envisioned.

In the casting of large ingots it is conventional to employ a substantially continuous process wherein a melt stock is melted into a cooled mold with the ingot formed therein being continuously withdrawn through an open bottom of the mold. Although the present invention is adapted to various types of casting and/or purification processes, the following description is referenced to the above-noted continuous ingot casting. For refractory casting it is common to employ a zone refining process; however, the present invention involves a substantially complete separation of stock and melt so that the process may be considered as an interrupted floating zone refining process.

In order to apply sufficient heat to liquify refractory materials so as to properly treat large volumes thereof, as for example, ingots of the order of one-half to one and one-half feet in diameter, it is advantageous to materially separate the electron beam source and the liquid pool and furthermore to fully accelerate the electron beam to high velocities without dependence upon the potential of the liquid pool or surrounding mold so that ionized gas or the like will not deleteriously affect the beam trajectory. This is herein attained without the disadvantages of metal "bridging" between stock and pool, whereby casting imperfections may result, and furthermore without sacrificing control, economy, or safety.

By the utilization of high voltage electron beams as the heat source in the casting method and means of this invention, former difficulties encountered in so-called "gas focusing" of electron beams is herein precluded. As an explanation of the foregoing it may be noted that despite continuous evacuation of a casting chamber as is herein contemplated, there is unavoidably present a certain amount of gas from the melted stock and, inasmuch as bombarding electron beams must pass through this gas, a tendency of the bombarding electron beams to direct themselves to the region of maximum gas density may be observed to produce "gas focusing."

In one presently preferred embodiment of this invention, there is provided an offset or substantially horizontal feed of melt stock in the casting process. A number of advantages result from the provision of horizontal feed, for it is therein possible to position the melt stock very closely above the mold into which same is adapted to melt and flow. The close spacing, or in other words, the small distance of fall or flow of the liquified melt stock minimizes the spattering of the metal as the same falls into the mold. Such minimized splattering of molten metal is highly desirable inasmuch as serious difficulties can arise from the deposition of metal upon structures around and about the mold and melt stock during casting operations inasmuch as physical dimensions and configurations of such structures may be thereby materially varied and, furthermore, the possibility of electrical shorts arises from such splattering. An additional advantage to be realized from offset or horizontal melt stock feed is the possibility of utilizing innumerable forms of melt stock. Thus, offset feed may be accompanied by the provision of suitable melt stock support means wherein the stock need not have particular properties of rigidity or strength so that consequently various melt stock compositions are readily adapted to the process. As employed herein "rigid" melt stock is taken to mean stock that is capable of supporting at least some portion of its length, such as a few inches thereof. For example, compacted powder or pieces of metal may be readily utilized as the melt stock in the present invention, although the structural strength of such melt stock is insufficient for certain other types of casting processes. Horizontal or offset melt stock feed, as is herein contemplated, is made possible by the focusing of high energy electrons into the open top of a mold from a plurality of different directions. For example, there may be provided a plurality of electron beam sources disposed at separated points to thereby direct the beams therefrom onto the mold top so as to not only bombard and melt the melt stock, but furthermore to provide an uninterrupted bombardment of the liquified metal in the mold. Orientation of the electron beam sources is limited to those relative dispositions wherein at least one electron beam fully undercuts the melt stock, i.e., bombards the entire liquid metal surface in the mold without possibility of blocking by the melt stock itself. By the provision of a number of electron beams undercutting the melt stock, the present invention precludes a serious difficuly in this type of casting, namely, "bridging." In the heating of melt stock it is possible for there to result a plastic flow of the melt stock material wherein such will depend from the stock and possibly eventually reach the mold disposed beneath same so that there then results a flow of melt stock material into the mold without a complete liquification of the melt stock. Although this circumstance may not be particularly troublesome in various casting operations wherein no particular purification of the metal is intended, in the present invention such difficulty is particularly serious for most certainly it is not possible to fully devolatilize the metal if same is not entirely melted. Undercutting of the melt stock so that any plastic flow thereof will be bombarded by high energy electrons to heat and melt same will be seen to fully remove the possibility of bridging between the melt stock and mold. As an additional advantage accuring to the present invention because of the offset melt feed thereof, there is found to be provided a material simplification of evacuation, for the resultant configuration of apparatus employed for offset melt feed does not interfere with full and complete communication between the casting region and the evacuation means.

The invention is illustrated in the accompanying drawing, wherein:

FIG. 1 is a diagrammatic representation of various steps in the casting process of this invention;

FIG. 2 is a schematic illustration in section of a furnace capable of carrying out the present invention;

FIG. 3 is a schematic illustration in section of an alternative furnace capable of carrying out the present invention; and

FIG. 4 is a schematic illustration in section of a furnace utilizing offset or substantially horizontal feed of melt stock.

In brief, the present invention may be stated to include the controlled melting of a melt stock by bombardment thereof with a high energy and high velocity electron beam established at a distance therefrom. The aforementioned electron beam is directed into a mold disposed directly beneath the stock to receive melted metal for further heating by the beam. All of the foregoing is carried out in a high vacuum maintained by continuous pumping whereby arc discharges are precluded and devolatilization of the metal is maximized. Although it is possible in accordance with the present invention to employ a single high energy electron beam for melting and further heating of the metal to be cast, yet it is highly advantageous in accordance with this invention to employ a plurality of electron beams whereby certain former limitations imposed upon bombardment casting by electron beams is entirely obviated.

Considering now the improved casting process of the present invention, reference is made to FIG. 1 of the drawing wherein separate steps of the manufacturing process are schematically illustrated. Casting is herein carried out with an initial or charge material in the form of a bar, rod, or the like, which will hereinafter be termed the melt stock **11**, and this melt stock is disposed in vertical displacement above an open mold **12** with the region therebetween being continuously evacuated, as by the illustrated pump **13**, to a high degree of vacuum. Although variations in the extent of vacuum employed in the process are possible, it is required that a relatively high vacuum be maintained, as of the order of 1.0 micron of mercury or less. Original melting and subsequent heating of the molten metal during the casting process is herein accomplished by electron bombardment, and thus as a further step of the present invention there is established a high energy electron beam **14** directed downwardly at an angle to vertical into the open upper end of the mold **12**. The melt stock **11** is then fed at a controlled rate vertically downward into the high energy electron beam, as illustrated at FIG. 1C, whereupon the edge of the beam impinges upon the melt stock and imparts sufficient energy thereto for melting of the stock. The melted stock, which may herein be considered to be a refractory metal, then drips or streams vertically downward into the open top of the mold **12** whereat the high energy electron beam imparts further heat thereto. The above-noted electron beam is generated at a substantial distance from the mold **12** and is formed of high velocity electrons with substantially the total energy thereof being imparted thereto at the generating location so that the beam energy is not dependent upon any particular potential of the mold or metal therein. A suitable plug or the like may be provided within the open mold **12** upon which the melted refractory metal drips or streams and suitable cooling is provided for the mold **12** so that the refractory metal is solidified therein.

The electron beam bombardment of the liquid metal within the top of the mold **12** imparts heat to the metal thereat to raise same to an elevated temperature and the metal may in fact be therein superheated. It will be appreciated that the melting of the melt stock **11** and the subsequent further heating thereof by electron bombardment will volatilize gases entrapped within the melt stock so that there is produced a substantial outgassing of the refractory material accompanied naturally by a substantial gas flow outwardly of the melt stock and liquid metal in the mold **12**. It is of particular importance in the casting of metals as herein contemplated that no arc discharge be established. The continuous evacuation of the region between the melt stock **11** and mold **12**, which is maintained throughout the process, serves to rapidly and efficiently remove the gases liberated from the molten metal. Even though these gases are rapidly removed from the vicinity of the mold and melt stock, a certain amount of ionization of the gas is produced above the mold, mainly by secondary electrons emitted from the metal. There is thus produced a plasma above the molten metal in the mold which tends to focus the electron beam or beams into the pool of metal. As the beam attains substantially full energy remote from the melt stock and metal pool, the beam is little affected by the melt stock or gases evolved therefrom so as not to curve into the full impingement upon the melt stock, as might otherwise occur. No low voltage beam deflection by gases, vapors, or ions can occur as same are not herein present at the remote beam generation location. Only high voltage effects are here present so that beam spreading and beam direction are more readily controlled.

There will be formed upon the upper surface of the metal deposited within the mold **12** a pool, generally in the form of a skull or concavity with molten metal above such concavity and solidified metal below same. The pool is maintained liquefied by energy of the bombarding beam, the shape thereof results in part from the fact the mold is preferably cooled by the passage of water through jackets formed therein. This molten liquid pool is maintained atop the metal deposited within the mold, and inasmuch as the maintenance of the pool is independent of the rate of melting of the melt stock, slow purification reactions can be carried essentially to completion therein. Furthermore, complete alloying can be produced in those instances involving slow rates of dissolution of one metal in another, for a continuous supply of heat at a controllable rate is provided to this pool from the high energy electron beam. A continuous process is herein accomplished by a withdrawing of the metal as same solidifies within the mold. An open lower end of the mold provides an egress aperture for metal which solidifies into an ingot **16** within the mold and beneath the liquid metal pool atop same. Either continuous or step removal of the ingot may be accomplished and ingots of any desired length may be attained thereby. In those instances wherein the melt stock has the same diameter as the mold opening, as for example, in reprocessing of ingots, it is herein desirable to provide not anly a vertical feed for the melt stock, but also a lateral adjustment therefor.

The reason for this will be apparent from a consideration of FIG. 1D wherein it will be seen that in order to insure dripping or streaming of the molten metal from the melt stock directly into the open end of the mold **12**, it is necessary to move the melt stock laterally toward the origin of the electron beam as the melt stock is lowered toward the mold. As metal is liquefied or melted off at a slant across the melt stock in the direction of traverse of the electron beam, the beam will first impinge upon a corner of the melt stock and, with progressive lowering of the latter, the drip point will be seen to move from one side of the melt stock to the other as the slant-line of melting moves across the stock. It is preferable for the melt stock to drip or stream generally into the mold adjacent the center thereof and thus only by laterally translating the melt stock is this possible when same has the same diameter as the opening in the mold **12**. In those instances where melt stock of smaller diameter than the mold opening are employed, it is not necessary to provide this lateral adjustment or translation.

As a modification of the above described casting process, there may be employed a plurality of electron beams rather than the single beam illustrated in FIG. 1 and discussed above. Thus, for example, a relatively large number of electron beams may be generated at points spaced laterally outward of the melt stock and focused into the upper open end of the mold **12**. In this manner it is possible to achieve a very high energy transfer to the molten metal in the pool atop the ingot **16** while at the same time limiting the necessary output energy of any individual electron beam source. This is particularly desirable in that conventional inexpensive beam sources may thereby be employed.

In the instance wherein a plurality of electron beams are employed, the electron velocity is yet maintained at substantially the same high level, for certain advantages of the present invention are dependent upon or at least resultant from such high electron velocities, as noted above. The advantage derived from a plurality of sources stems in part upon the fact that electron density from an individual source may thereby be decreased with the composite electron density at the surface of the molten pool being, however, quite substantial in view of the fact that a large number of beams intersect thereat. In accordance with conventional practices, it is highly desirable when employing a plurality of intersecting electron beams to direct such beams at a relatively large angle of intersection in order that the distance or extent of beam intersection or cross-over may be minimized. A beam angle of 45 degrees from vertical has been found to be suitable. Electron beam interaction is held to a minimum by the foregoing and also by the provision of a very substantial electron beam velocity wherein the probability of mutual deflection is minimized. A further advantage to be realized from the utilization of a plurality of high energy electron beams is the omission of any requirement for lateral movement of the melt stock inasmuch as the melt stock may in such cases be fed only vertically downward toward the mold **12**.

It has been found that casting operations performed

in accordance with the above described process provide a molten metal pool on the top of the cast ingot which has a substantially or relatively quiescent surface. This is highly desirable in casting operations for it thus follows that continuous ingot casting can thereby be performed. The continuous evacuation employed throughout the process of the present invention removes not only a substantial portion of the normally present gaseous molecules from the vicinity of the operation, but also removes gases and the vapors liberated during the original melting of the melt stock. Thus, the liquid pool formed at the top of the cast ingot does not contain the normal amount of occluded gases. Such gases as may yet be retained within the molten metal are further volatilized and liberated therefrom by the addition of heat to the liquid metal from the bombarding high energy electrons directed upon the pool. Because of the relatively low order of occluded gases within the metal forming the liquid pool, the process hereof proceeds without large gas bursts from the surface of the pool as are normally encountered. Consequently, liquid metal is not sprayed about the area above the liquid pool by gas bursts to thereby coat adjacent structure and interfere with the casting process. Previously encountered operational difficulties normally requiring periodic shut-downs in casting processes are thereby herein precluded. Furthermore, the relatively quiescent pool surface allows relatively insoluble impurities to float upon the surface of the melt without mixing with the body thereof so that inclusion-free ingots are produced. Additionally, the relatively large temperature difference existing between the cooled mold and the heated pool surface induces substantial thermal gradients within the liquid melt to thereby produce an intense stirring action which aids in bringing volatile impurities to the surface of the melt. Such volatile impurities, upon reaching the melt surfaces, are volatilized by the high temperature thereat and consequently removed from the melt so that the resultant ingot is substantially free of gases and impurities having low volatilization temperatures.

The above described casting process, employing remotely generated, high energy electron beams directed at an angle into a mold for both melting and further heating melt stock, all in a highly evacuated atmosphere, produces cast materials having properties hitherto unknown in the art. Not only is it possible with the present invention to economically cast refractory materials such as columbium, molybdenum, tantalum, and tungsten, but also it is possible to purify these materials into such a state that their utility is materially improved. Thus, the ductility of refractory metals cast and purified by the present invention is markedly superior to those prepared in other manners. Furthermore, the resistance to environmental attack and the physical properties at high temperatures has been found to be substantially improved by the processing of such metals in accordance with the present invention. Although this invention is particularly adapted to the purification and casting of refractory metals, yet also highly desirable results are attained with the present invention in the casting of other alloys. Thus, for example, the electron beam melting of iron, nickel, and cobalt based alloys has been found to remove certain critical impurities, apparently sulphur and phosphorous, to thereby eliminate differences in transverse and longitudinal properties in forged billets thereof. Such alloys processed in accordance with the present invention have been found to be highly ductile in comparison to those prepared in other manners and furthermore to have significantly higher strength to thereby extend their range of utility into such fields as those of misslie construction. A further limitation of the prior art is overcome by the present invention in that it is herein possible to produce ingots of great size, not only of common alloys but also of refractory metals and refractory metal alloys which have historically been limited to small dimensions.

Considering now individual structure and apparatus in accordance with the present invention and adapted to carry out the above described process of this invention, reference is made to FIG. 2 of the drawing wherein there is illustrated an electron beam furnace **21** comprising, in part, an enclosure or housing **22** having evacuation means **23** communicating therewith and including high-speed and low pressure pumping apparatus. Within the housing **22** there is provided a mold **24**, formed of copper or the like, and having a central opening **26** therethrough. This mold **24** is adapted to be cooled, as for example, by water circulating within a jacket **27** therein and connected, as by pipes **28** and **29**, to a cooling system circulating such as water through the jacket **27**. In vertical displacement above the mold **24** there is disposed a melt stock **31**, which in this instance may, for example, comprise a refractory metal in the form of an elongated cylindrical rod. The melt stock is mounted within suitable mechanism **32** adapted to feed the stock vertically downward toward the mold **24** at a controlled rate and also to provide such lateral translation or adjustment of the melt stock as may be desired. Suitable sealing means **33** prevent the loss of vacuum from the interior of the housing **22** about the drive mechanism **32**. Heat is provided in the furnace **21** for the purpose of melting the melt stock and subsequent additional heating of the melt in the mold **24** by the generation of at least one high voltage and high energy electron beam. To this end there is provided an electron beam source **34** extending at least in part into the interior of the chamber **22** and suitably sealed at the wall thereof to preserve vacuum within the housing. The electron beam source **34** may be energized from conventional power supply and control means **36** located, for example, outside the housing and the source produces a focused electron beam **37** directed into the open end of the mold **24**. As previously noted, the source produces a high voltage electron beam **37** which is thereby relatively uninfluenced by such gaseous atmosphere or ion clouds as it may be called upon to pass through in its trajectory to the top of the mold **24**.

Operation of the furnace as described above is accomplished by feeding the melt stock **31** vertically downward toward the mold **24** so as to enter the electron beam path. As the melt stock **31** is fed into the electron beam **37**, energy is imparted to the melt stock whereby same is liquidfied and drips or streams from the bottom thereof vertically downward into the open top of the mold **24**. Operation is initiated with a plug or the like, not shown, inserted in the mold opening **26** and upon which the molten metal from the metal stock **31** deposits. As the molten metal within the mold **24** solidifies by extraction of heat therefrom to the cooling medium circulated through the mold jacket **27**, the solidified metal in the form of an ingot **38** is withdrawn through the bottom of the mold **24**, so that there is herein produced a continuous casting process. The electron beam bombarding the metal dripping or streaming into the opening **26** in the mold **24** serves to further heat this metal and there is thus formed at the top of the ingot **38** a liquid pool **39** of molten metal which is generally defined by a concave undersurface **41** marking the line of solidification of the metal. The melt stock **31** is melted off at an angle, as illustrated in FIG. 2, to drip into the pool **39** as the melt stock is fed downward into the electron beam **37**. Suitable lateral adjustment of the position of the melt stock **31** may be accomplished by the drive mechanism **32** as required to maintain the dripping or flowing of the molten stock into the opening **26** in the mold **24**. Continuous high-vacuum pumping is carried out throughout the casting process to remove gases liberated during melting and subsequent heating of the material cast. The liberation of vapor and gas at the surface of the pool **39** from the further heating thereof and the consequent ionization at least in part of such vapor and gas, thereby forms with the electrons an electrical plasma about the top of the pool to additionally focus electrons into the pool. By the provision of a high velocity to the electron beam **37** at a substantial distance form the melt stock, the beam is not materially affected by gas or ions or the relative potential of the melt stock **31** so that the melt stock exerts almost no electrical influence upon the beam but instead affects the beam only by interception of some small portion thereof as the melt stock is fed into the beam.

An alternative furnace structure is illustrated in FIG. 3, and reference is made thereto with regard to the following brief description. In this embodiment of the furnace of the present invention, similar elements are numbered the same as in the previously described embodiment. The vacuum tight housing **22** is herein again provided with suitable evacuation conduits **23** adapted for attachment to high speed pumping apparatus, and there is provided an open mold **24** vertically displaced below an elongated melt stock **31** which is adapted to be fed vertically downward toward the open upper end of the mold **24** in sealing relation to the walls of the housing. A first electron beam source **34** is disposed similarly to the one described above with an electron beam **37** generated therein and directed into focus upon the mold **26** at the upper open end thereof. In this instance a second electron beam source **34'** is disposed in extension through the wall of the housing **22** and, upon energization from suitable and conventional power supply control means **36'**, generates a high velocity electron beam **37'** which is directed upon the upper open end of the mold **24**. In the instance wherein but two electron sources are employed, as illustrated, such sources are preferably located on opposite sides of the melt stock **31**; however, should a larger plurality of beam sources be employed, same may be disposed in a circle, for example, about the melt stock and all directed to focus the beam therefrom into the open end of the casting mold. Although each of the electron beams is illustrated in FIG. 3 as being directed exactly into the mold top and as fully crossing over each other, the plasma formed immediately above the pool actually modifies this to a certain extent in that some beam deflection therein occurs and a focusing of the beams into the pool results. In this furnace structure, vertical feeding of the melt stock **31** downward toward the mold **24** moves the melt stock into the path of both of the electron beams **37** and **37'**. The electron beam sources **34** and **34'** are preferably disposed in equal separation from the axis of the melt stock **31** so that therefore the electron beams **37** and **37'** focused upon the mold **24** will equally impinge upon the melt stock **31** lowered into the beams to consequently melt off equal portions from opposite lower corners of the melt stock.

As described above in connection with the improved casting process of the present invention, there is produced at the top of the solidified ingot **38** within the mold **24**, a pool of molten metal **39** which is additionally heated by the impinging high energy electron beams whereby further devolatilization occurs thereat. In the multi-gun furnace illustrated in FIG. 3, the multiplicity of electron beam sources materially reduces the requirements of each source. Thus, although each electron gun is required to produce an electron beam with a relatively high electron velocity, the beam current need not be large in any individual gun. Various types of electron guns may be employed in a multi-gun furnace of the type described above and thus, for example, there may be utilized electron guns of the type generally employed in electron microscopes or, alternatively, those types of electron guns employed in oscilloscopes and television videoscopes with suitable focusing for directing the relatively high velocity beam upon the pool of molten metal at the top of the ingot within the mold.

Considering the improved offset-feed casting method shown in FIG. 4, same is carried out in an evacuated chamber which is continuously pumped to a high vacuum of the order of 1.0 microns of mercury or less pressure. Casting may be accomplished in a water-cooled mold having an opening entirely therethrough from top to bottom, in the instance wherein a continuous ingot casting process is desired. A melt stock, formed for example, of tungsten of normal purification, is fed toward the axis of the aforementioned mold from the side of the mold and above same. There is thus provided an offset relation between the melt casting and mold wherein the melt casting is moved at a controlled rate toward the mold above same. Preferably, the separation between mold and melt casting in a vertical direction is maintained quite small in order that liquid metal melted from the melt stock and dripping or streaming therefrom into the mold will not splatter when it impinges upon the metal within the mold. Heating of the melt stock for melting of same is accomplished by bombardment of the forward end of the melt stock with high voltage electrons generated and accelerated as in the form of a beam at a point remote from the melt stock and mold and directed into focus in the top of the mold. It is to be noted at this point that the above described electron beam is generated at a substantial distance from the mold and melt stock and, furthermore, that the electron beam so generated is fully accelerated at a point remote from the melt stock and mold in order that low voltage beam effects will be herein precluded. It will be appreciated from the foregoing description of the relative location of the electron beam source and the melt stock and mold, that the electron beam source is of necessity disposed above the mold. Additional high voltage electrons are directed into the top of the mold from different directions, and to this end there may be further provided a plurality of other electron beam sources individually producing high voltage electron beams at a plurality of separate points remotely spaced from the mold. The electron beams of each of the sources are directed upon the open top of the mold and are focused thereat to substantially cover the open mold surface. A natural and unavoidable divergence of the electron beams is herein encountered and such is taken advantage of by so positioning the electron beam sources and energizing the electron beams in such a manner that the spread electron beam has substantially the same or greater cross section as the open mold top at the intersection with the beam at such top. Although it was above stated that a single electron beam is employed to heat and consequently melt the metal of the melt stock, yet it is possible for more than one beam to impinge upon the forward end of the melt stock to thereby additionally heat same. As previously noted, the melt stock is fed in a direction toward the mold and above same, and the high velocity electrons are directed and oriented to impinge only upon the forward end of the melt stock above the mold so that melting metal will only fall off within the mold. At least a portion of the electrons, as in the form of electron beams, fully undercuts the melt stock in such a manner as to be focused upon the top of the mold without possible obstruction or interference from the melt stock. It has been found that the plurality of electron beams may be advantageously directed downward at an angle of about forty-five degrees to vertical from points spaced about a circle above the mold. Certain metals having particular and unusual melting characteristics modify the optimum beam angle for melting of the metal and thus tantalum, for example, requires a more vertical beam trajectory for melting of same, inasmuch as this metal tends to liquify at a distance from the end upon bombardment at beam angles as large as forty-five degrees.

Feeding of the melt stock in a lateral direction toward the mold above same so as to intersect one or more of the electron beams focused into the mold will produce a heating of the forward end of the melt stock so that same

consequently melts and either drips or streams downward into the open mold. The further application of heat to such metal falling from the melt stock into the mold will maintain a pool of liquid metal within the mold. In the instance wherein a continuously cast ingot is desired, the mold is normally cooled and the metal falling therein is gradually withdrawn from the bottom of the mold as same solidifies. There is maintained at all times at the top of the metal solidifying within the mold a liquid pool of molten metal into which metal from the melt stock flows upon melting by electron beam bombardment. The application of additional heat to this liquid metal pool from the multiplicity of electron beams focused therein serves to further controllably heat the liquid metal so as to consequently promote devolatilization of same and to additionally promote the completion of alloying processes wherein an extended time period is required for the dissolution of one metal into another. In this respect, note that the heating of the metal in the mold is independent of the rate of flow of metal from the melt stock and of the rate of feed thereof into the beam. A large amount of gas is normally liberated from the melt stock as same is liquified and, in accordance with the above noted evacuation, such gases are rapidly withdrawn from the reaction chamber. Additional gas and vapors will rise from the additionally heated metal pool in the mold and these also are removed from the chamber by the evacuation system. Because of the initial vacuum condition and the continued removal of gases from the melt stock as same is liquified, the amount of gas and vapor evolved from the liquid pool upon further and additional heating thereof from the bombarding electron beams is not as great as it would otherwise be. In particular, it has been found that almost no gas bursts are encountered in the liquid pool, contrary to arc heating processes. It has in fact been observed that the surface of the liquid pool is relatively quiescent so that impurities in the liquid metal which are lighter than the metal itself will float upon the top of the pool and will not be violently agitated so as to remix with the solidifying metal at the bottom of the pool. There are, however, established substantial stirring currents in the pool as a result of the thermal gradients therein, and consequently volatile impurities tend to be moved to the pool surface whereat the temperature is at a maximum and consequently the impurities are more readily volatilized to leave the liquid metal in the form of gases and vapors which may then be withdrawn from the area by the evacuation thereof.

Although the above described casting process has been stated to employ a large plurality of separate electron beams it will, of course, be appreciated that an important requirement, insofar as electron beam bombardment is concerned, is the necessity of undercutting the melt stock and also of providing, in addition to melt stock bombardment, a separate and continuous bombardment heating of the molten metal in the mold. It is possible to accomplish these requirements with a single materially elongated electron source of the type disclosed, for example, in our copending patent application Serial No. 818,306 for Electron Beam Generation. Thus, the electron generation may be more generically defined as including the acceleration of electrons and the focusing of same into the molten metal in the mold from a plurality of directions with at least a portion of such accelerated and focused electrons being directed upon the molten pool at such an angle as to be free of interference by the melt stock itself. In this manner it will be seen that bridging between the melt stock and mold is equally well precluded.

It has been found that material cast in accordance with the above process exhibits remarkable and improved properties. Thus, for example, in the casting of iron, nickel and cobalt based alloys there have been produced ingots wherein no observable deposits at grain boundaries are present and wherein forged billets of material so processed have no directional properties. Thus, in addition to the normal casting requirements of minimizing the formation of substantial voids and the deposition of substantial amounts of impurities, the process of the present invention operates to purify the metal itself in addition to merely casting same. The ductility of refractory metals, for example, cast in accordance with the foregoing process is found to be materially enhanced. Materials purified and cast in accordance with the present invention may be readily worked as by normal machining operations, which were hitherto impossible with many types of metal. In addition then to a casting process, the present invention actually comprises a purification process equally applicable to very high temperature metals of the refractory class as well as to other more conventional metals.

Referring to FIG. 4, there is provided as a part of the furnace **111** a vacuum tight housing **112** defining therein a chamber **113**. A suitable evacuation system **114** is connected in full communication with the chamber **113** and operates to rapidly remove gases evolved within the chamber and further serves to maintain a substantial vacuum within the chamber, as of the order of 1.0 microns of mercury or better. At the bottom of the housing **112** there is disposed a mold **116** formed of copper preferably, and having a central opening **117** therethrough communicating with the exterior of the housing. The mold **116** includes a cooling jacket which may have water or other cooling media circulated therethrough as by means of the inlet pipe **118** and outlet pipe **119** connected to a suitable cooling system. Also within the housing **112** there is provided a melt support trough or table **121** which is preferably rigidly affixed within the housing, as by suitable support means, and which is itself cooled as by the circulation of water or other cooling medium through passages therein or pipes adhering thereto and supplied through cooling pipes **122** extending from the support means **121** outside of the housing **112** for connection to a suitable source of coolant. The table **121** is disposed at one side of the mold **116** and extending in part above same, although terminating short of the vertical extension of the mold opening **117**, as illustrated. The melt support means **121** is preferably disposed in an either horizontal or inclined position to one side of the mold and is adapted to carry thereon a melt stock **123** which may take the form of a rod or bar or other convenient physical configuration. This melt stock may, for example, be an ingot of metal which has previously been cast or may alternatively be formed of a sintered material including both powder and pieces of the metal to be cast. In order to maintain the process of the present invention continuous, there is herein provided an air lock **124** disposed in communication with the interior chamber **113** and extending through the housing **112** to the exterior thereof whereby the melt stock may be inserted into the chamber **113** without loss of vacuum therein. There is additionally provided melt stock feed means **126** which may extend through the air lock **124** and may include drive means controllable from the exterior of the furnace for moving the melt stock upon the support means **121** at a controlled rate. After initial charging of the mold **116**, wherein a plug may be employed to close the opening **117** therethrough, the mold is normally filled with an ingot **127** which is continuously withdrawn through the bottom of the mold as by means of an ingot puller **128**, suitably energized.

As a further portion of the improved casting furnace of the present invention there are provided a plurality of electron beam sources, herein illustrated as three sources **131**, **132**, and **133** assumed to include power supplies and control circuitry. These sources are adapted to produce high voltage electron beams **136**, **137**, and **138**, respectively, which are directed toward the mold **116** and are, in fact, focused into the opening **117** therein. The individual sources are disposed above the mold **116** and are oriented in relatively spaced relationship so as to direct the individual beams thereof into the mold from separate directions, as for example, from points upon a circle above and about the mold. Each of the electron beams **136**, **137**, and **138** will be seen to individually diverge in a normal and conventional manner and to be directed onto the top of the ingot **127** in the mold **116** at an angle to vertical. At least one of the electron beam sources **133** is disposed to direct the beam **138** thereof onto the mold **116** at such an angle as to intercept the forward end of the melt stock **123** as same is fed toward the mold above same. Bombardment of the forward end of the melt stock **123** with the beam **138** will impart energy to the melt stock for heating same whereby the stock is melted and liquid drops or streams thereof will flow downward from the projecting end of the melt stock into the opening **117** in the mold **116**. It should be noted that beam **138** is directed along a line which extends downwardly and inwardly from the melt stock to the mold. Thus, beam **138** melts off the inner end of the melt stock along an inwardly and downwardly extending direction to provide a sharp drip point and reduce the load on the overhanging part of the melt stock. The rate of feed of the melt stock **123** toward the mold, or in this instance into intercepting relationship with the electron beam **138**, is controlled so that the melt stock does not move into the beam faster than the latter can impart energy to the melt stock for liquifying same.

In addition to the interception or bombardment of a moving melt stock **123** with one or more of the electron beams generated by the electron beam sources, at least one of the electron beams, herein illustrated as the beam **136**, is directed onto the top of the ingot **127** in the mold **116** at such an angle as to remain entirely clear of the melt stock and to be incapable of being intercepted even in part by same. This electron beam **136** may then be considered as undercutting the melt stock or, in other words, as passing beneath same into the mold so that any plastic flow of the melt stock in a vertically downward direction toward the mold as may be the result of melt stock heating, cannot bridge the gap between the melt stock and mold without being intercepted by the beam **136** and thereby liquified. Liquid melt stock dropping or flowing from the melt stock **123** into the mold will, as noted above, be solidified within the mold by the cooling action of the coolant traversing the water jacket of the mold. There is, however, maintained atop the ingot **127** formed within the mold **116**, a molten pool **139** of metal which is heated by electron bombardment. This molten metal heating will be seen to be entirely independent of the heat applied to the melt stock **123** and consequently there is provided by the present furnace a further or additional controllable heating of the metal whereby devolatilization thereof is furthered, and, additionally, whereby alloying operations may be continued for an appreciable period of time. Liquification of the melt stock **123** by bombardment with one or more of the electron beams is accomplished by the application of heat to the melt stock and such heat will of course in part be conducted to the support means or table **121**. The additional heat imparted to the table **121** is carried away by a coolant passed through the tubes **122** and through the table **121**, as illustrated.

Charging of the furnace is readily accomplished by placing melt stock within the air lock **124** and engaging the feed means **126** thereto, whereupon the melt stock is controllably fed or driven into the chamber **113** and thence into intercepting relationship with one or more of the bombarding electron beams whereby the melt stock is melted to fall into the mold and thereby form an ingot in the opening **117** therein. It is herein contemplated that in addition to straightforward casting operations, the furnace of the present invention may be employed to purify metal cast therein for, as above noted in the description of the process of the present invention, not only is the material cast into an ingot but also occluded gases and volatile impurities are driven from the metal and are rapidly removed by the evacuation system **114**. Extremely pure metals may be obtained by use of the furnace hereof by recycling. Thus, the ingot **127** may, upon withdrawal from the furnace, be employed as a melt stock and run again through the furnace whereby the metal is again melted and purified.

As noted above, particular advantage is derived from the remote location of the electron gun or guns of the present furnace, for difficulty formerly encountered in focusing or directing the electron beam within the required narrow limits is herein obviated. With close cathode structures it is possible for evolved vapors to modify the electron flow direction before the electron beam or electrons of the beam have received their full kinetic energy, inasmuch as these vapors modify the cathode to anode space-charge in such configuration. In the present invention the electron beam is raised to full energy in a wholly evacuated area entirely away from gas contaminating influences, for the remote location of the electron beam source precludes divergence of evolved gas to the generating area. Of additional note herein is the direction of electron beam trajectory relative to the other components of the apparatus or, in other words, to the direction of flow of molten metal. Although it is possible in other furnace structures to employ electron beam sources, difficulty is universally encountered therewith because of the inability of such beam source to both melt the melt stock and to further heat the entire liquid pool of molten metal produced therefrom. As previously noted, it is of great advantage to provide additional heating to the molten metal to the end of furthering devolatilization reactions.

In the present invention there is provided a high energy electron beam directed at an angle to vertical whereby the electron beam not only melts the melt stock by partial impingement upon same and also heats the ingot top by direct bombardment, but, furthermore, fully passes between the melt stock and ingot to thereby preclude metal bridging between same. In electron beam bombardment furnaces it is possible for metal to flow into the mold without full liquification thereof unless provision is made for maintaining a high temperature between melt stock and mold or for otherwise fully melting any melt stock before same can enter the mold. In the present invention there is not necessarily maintained a high temperature between the melt stock and ingot, yet there is provided between same a high energy electron beam such that should there be located any solid object or objects in such space, same will be bombarded by the electron beam to materially raise the temperature thereof and melt same. Thus, the present invention operates to preclude "bridging" between the melt stock and ingot.

What is claimed is:

1. A method of casting a melt stock material in a mold open at its top to hold a pool of molten material, and being located in a chamber, the method comprising disposing a rigid melt stock over the mold in close proximity to the top thereof to leave a vertical space between the melt stock and the pool of molten material in the mold, generating an electron beam in the chamber at a location remote and upwardly displaced from said vertical space, accelerating the beam at said location independently of the mold and the melt stock, directing the beam at an angle to the vertical and into the open top of the mold so a portion of the beam traverses the vertical space between the melt stock and upper end of the mold from one side of the mold to the opposite side of the mold and maintains the molten pool of material in the upper portion of the mold, advancing the melt stock into the beam at a rate so a portion of the beam strikes and melts the melt stock along an inclined surface to liberate gas and cause molten material to drip from a lower edge of the inclined surface of the melt stock maintained above the mold and fall freely through the said vertical space into the molten pool in the top of the mold, and so a portion of the beam continues to traverse the vertical space and heat falling molten material to aid in the additional liberation of gas and prevent mechanical bridging between the melt stock and the upper end of the mold, and simultaneously evacuating the chamber to remove gas liberated from the heated melt stock.

2. The method according to claim **1** which includes the step of moving the melt stock downwardly into the beam of electrons at a controlled rate to continuously melt the melt stock over the mold.

3. The method according to claim **1** which includes the step of controllably moving the melt stock downwardly and laterally with respect to the vertical into the beam of electrons.

4. The method according to claim **1** which includes the step of forming a plurality of electron beams at locations remote and upwardly displaced from said vertical space, accelerating them at said locations independently of the mold and melt stock, and directing the beams at different angles into the top of the mold.

5. A casting method comprising disposing a rigid melt stock above a mold open at its top and containing molten material, said melt stock having a greater lateral dimension than the open mold top and being disposed adjacent and spaced above the mold, bombarding the upper portion of the mold with a beam of high velocity electrons from a source fully energized remotely from and independently of the mold and melt stock to maintain a molten pool in the top of the mold, moving melt stock laterally into said beam between the electron source and the mold pool so the melt stock is progressively heated and melted directly over the open top of the mold by electron bombardment from part of the beam to drip through free space into the mold from a lower edge of the stock maintained over the mold by a controlled rate of stock movement, directing a portion of the electrons at an angle to pass completely across the top of the mold and under the portion of the melt stock above the mold to prevent bridging between the melt stock and molten metal in the mold, and simultaneously evacuating a region encompassing the upper portion of the mold and overlying portion of the melt stock.

6. A casting method comprising disposing a rigid melt stock on an elongated support disposed above and laterally offset from a mold open at its top and containing molten material, a portion of the support being adjacent and spaced above the mold, bombarding the upper portion of the mold with high velocity electrons from a plurality of sources fully energized remotely from and independently of the mold and melt stock to maintain a molten pool in the top of the mold, moving the melt stock substantially horizontally over the support to a location spaced above the mold and molten pool and between the electron source and the mold so the melt stock is heated by electron bombardment, becomes molten and drops into the mold, directing a portion of the electrons at an angle so some hit the front end of the melt stock and others pass completely across the tip of the mold and under the melt stock above the mold and prevent bridging between the melt stock and molten metal in the mold, directing another portion of the electrons downwardly at an angle to vertical into the mold from above the melt stock to melt an inclined surface on the leading edge of the stock with molten metal dripping from the lower edge thereof into the mold, and simultaneously evacuating a region encompassing the upper portion of the mold and overlying portion of the melt stock.

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