

July 13, 1965

D. H. LANE ETAL

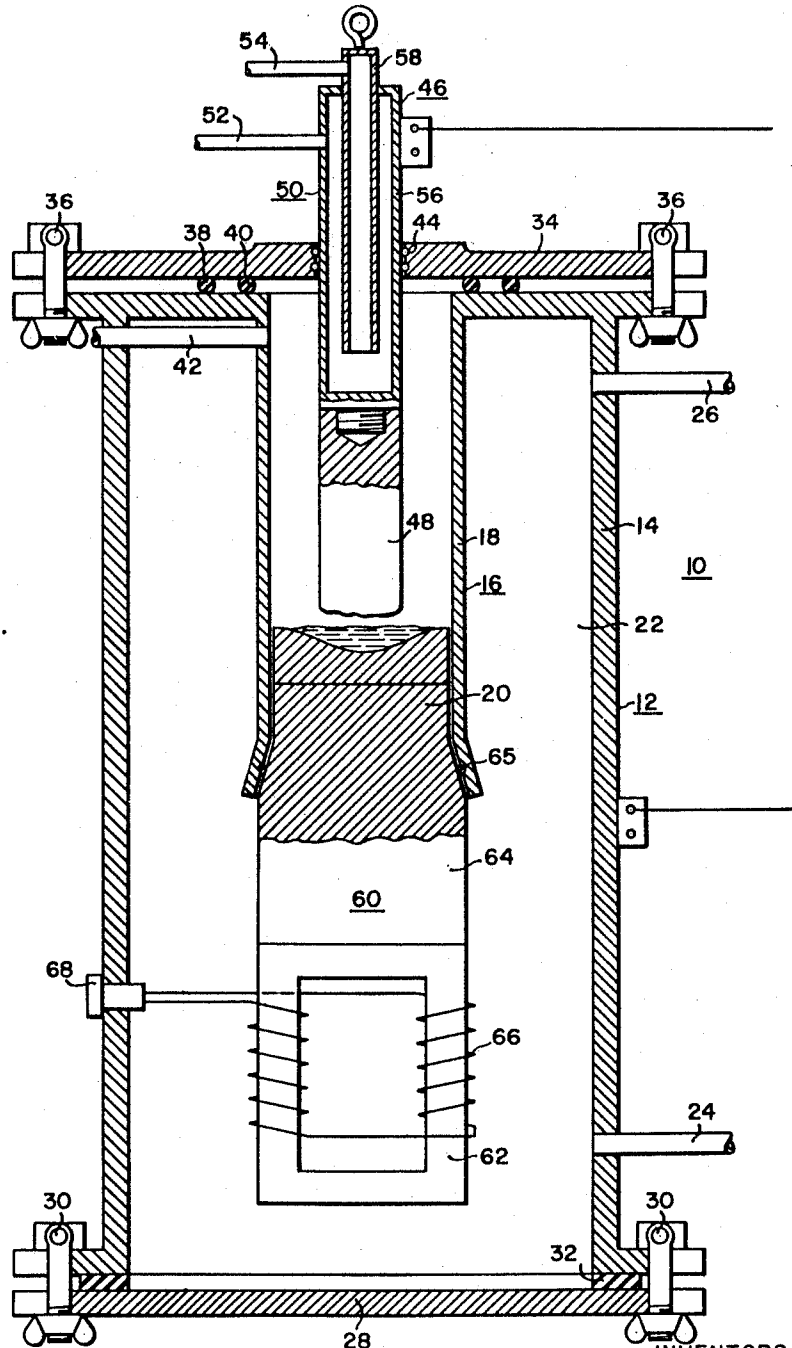
3,193,889

METHOD AND APPARATUS FOR PRODUCING UNIFORM
GRAIN REFINEMENT IN METAL INGOTS

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3 Sheets-Sheet 1

Fig. 1.



WITNESSES

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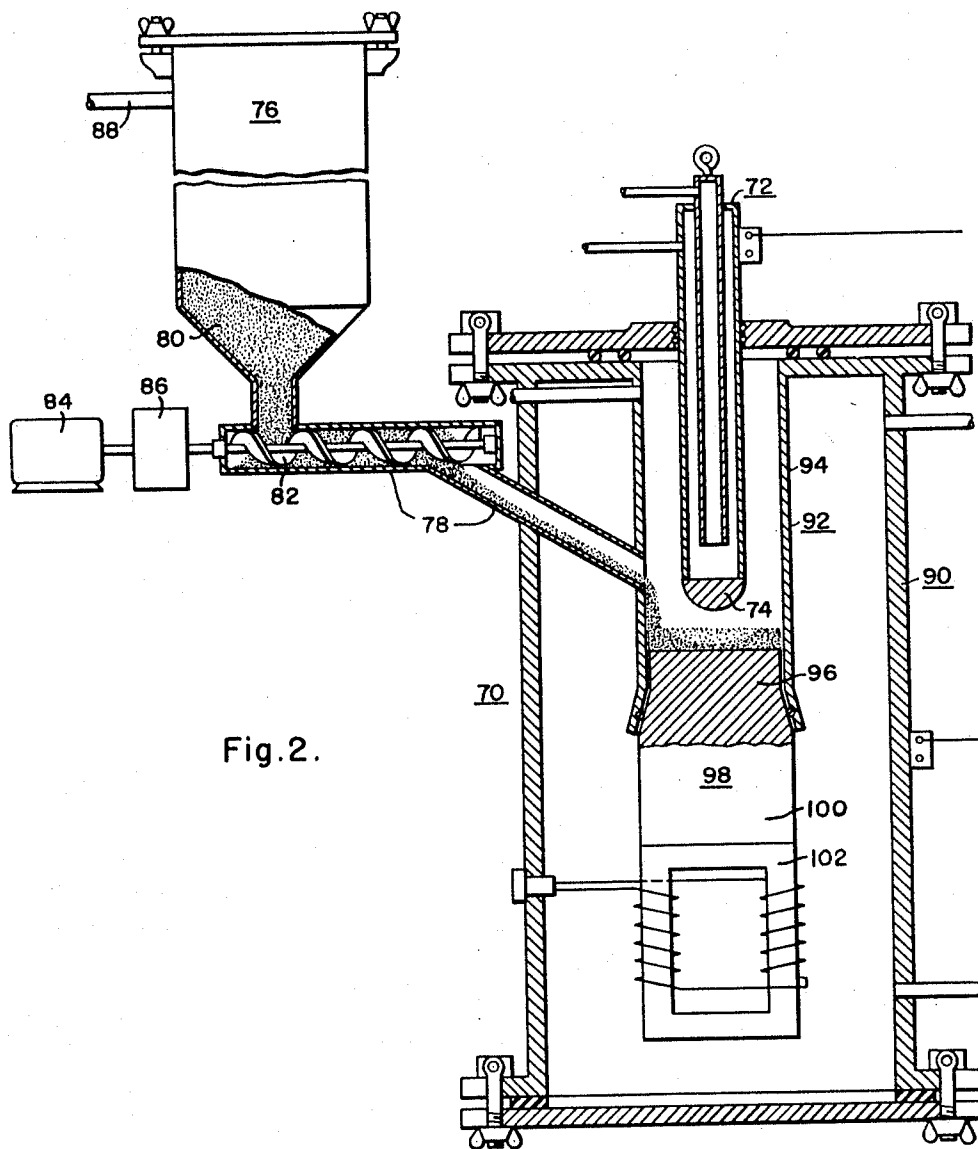
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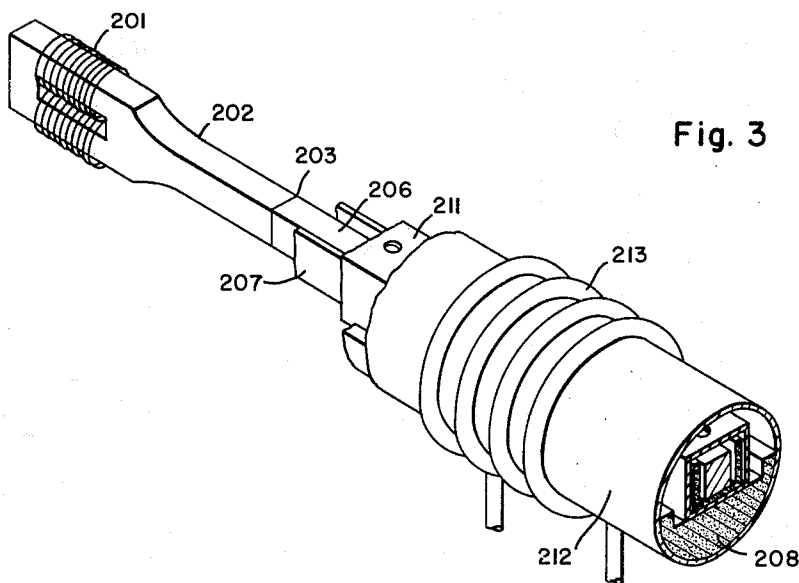
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3,193,889

METHOD AND APPARATUS FOR PRODUCING
UNIFORM GRAIN REFINEMENT IN METAL
INGOTS

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6 Claims. (Cl. 22—61)

This invention relates to methods and apparatus for producing sound homogeneous metal ingots of substantially uniform grain size.

This application is a continuation-in-part of application Serial No. 788,646, filed January 23, 1959, now abandoned, for "Method and Apparatus for Forming Ingots."

In particular this invention relates to an apparatus and process for melting furnaces by providing an ultrasonic transducer unit so positioned and utilized as to provide optimum transfer of sonic energy to molten metal during solidification thereof whereby an ingot produced thereby has a refined grain structure throughout.

It has been proposed heretofore to employ vibration in the form of sonic and ultrasonic energy to produce metal ingots having improved metallurgical properties. Thus, for example, ultrasonic transducer stacks have been mechanically attached to the side walls of a melting crucible or ingot mold in an effort to transmit the ultrasonic energy to the melt. This method, however, has not proved effective or efficient for the production of relatively large size ingots.

Also it has been proposed to introduce ultrasonic energy into a solidifying melt by means of a wave transmitting coupling bar attached to the transducer stack. The wave transmitting coupling bar which must be prepared from a material having a substantially higher melting point than the metal to be solidified is dipped into the melt to introduce mechanical vibrations into the melt during solidification thereof. This method has not proved effective for many reasons. While small ingots of low melting point metals have been so treated, no satisfactory ingots of high melting point metals such as iron and steel have been produced to the best of applicants' knowledge. The ultrasonic energy is substantially reduced in intensity and effectiveness at the areas farthest from the energy source (the attenuation of the sound intensity is an exponential function of distance from the source), and the sound waves may be heavily damped by liquids. Thus, in producing ingots of relatively large size, this method will usually be effective only within the immediate volume surrounding the coupling bar leaving most of the melt, during solidification, substantially unaffected by the sound waves.

The above prior art methods of ultrasonic vibration of molten metals have relatively enormous energy requirements which exceed practical limits for ingots of commercial size; i.e., six to twelve inches in diameter and greater.

This invention is directed to apparatus and methods for producing sound homogeneous ingots, particularly massive ingots, by the use of sound energy, which apparatus and methods eliminate many of the problems heretofore encountered in the prior art practices.

The object of this invention is to provide an electric arc-melting furnace capable of producing sound homogeneous ingots comprising an elongated crucible comprising side walls and a bottom closure, a melting electrode, and an ultrasonic transducer unit comprising a wave transmitting coupling bar and transducer stack attached to the bar, the wave transmitting coupling bar of the

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transducer unit being integral with the bottom closure of said elongated crucible whereby ultrasonic energy is directly transmitted from the transducer stack through the said wave transmitting coupling bar and thence directly to molten metal deposited on the bottom closure during the operation of the arc melting furnace.

Another object of this invention is to provide a method for producing massive sound homogeneous metal ingots having improved grain structure throughout which method comprises arc-melting a metal out of contact with a reactive gas, depositing the molten metal in successive continuous increments upon a crucible base while applying ultrasonic energy directly to the base whereby to provide for effective and efficient vibration of the molten metal with relatively low energy input during solidification thereof.

A further object of the invention is to provide a method for the efficient sonic vibration of molten metal at the freezing solid-liquid interface at relatively low power input, comprising irradiating the interface with ultrasonic waves through a continuous path consisting essentially of metal in the solid state, whereby a high degree of grain refinement throughout the resulting ingot is achieved.

Other objects of this invention will, in part, be obvious and will, in part, appear hereinafter.

For a better understanding of the nature and the objects of this invention reference should be had to the following detailed description and drawing, in which:

FIGURE 1 is a view, partly in section, showing an apparatus for producing massive metal ingots embodying the ideas disclosed by this invention;

FIG. 2 is a view, partly in section and partly in elevation, of apparatus embodying this invention; and

FIG. 3 is a view, partly in section and partly in perspective of an experimental melting furnace.

In accordance with one aspect of this invention there is provided an electric arc-melting furnace comprising an elongated crucible comprising side walls and a bottom closure, a melting electrode and an ultrasonic transducer unit. The ultrasonic transducer unit is composed of a wave transmitting coupling bar and a transducer stack attached to the bar. The wave transmitting coupling bar of the transducer unit is integral with the bottom closure of the crucible and ultrasonic energy is directly transmitted through the coupling bar to the bottom closure and thence directly to molten metal deposited on the bottom closure or solidified ingot during operation of the arc melting furnace.

In the preferred embodiment of this invention a portion of the wave transmitting coupling bar serves as the bottom closure or base of the crucible, whereby effective and efficient sonic energy is delivered to the molten metal during ingot production. The apparatus and methods of this invention provide for the most efficient and effective use of the ultrasonic energy at relatively low energy input during ingot production, and sound homogeneous metal ingots of substantial size and having substantially uniform equiaxed grain structure have been produced. A practical lower limit of electrical energy input is 0.25 watt per square centimeter at normal melting rates.

The invention may be applied to various metals such, for example, as ferrous metals including stainless steel and carbon steel, aluminum and its alloys, nickel, cobalt and iron base alloys, zirconium, molybdenum, and titanium and their alloys.

Referring to FIG. 1 of the drawing there is shown an electric arc-melting furnace 10 which comprises a container 12 having side walls 14. Inside the container 12 there is disposed an arc-melting crucible or ingot mold 16 comprising side walls 18 and a bottom closure 20. A reservoir space 22 is provided between the crucible 16 and the outer walls of the container 12 for receiving

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water which may be introduced through water inlet 24 and withdrawn through water outlet 26.

The side walls 18 of arc-melting crucible 16 may be of any material having a high heat conductivity and a moderately high melting point such, for example, as copper.

The container 12 is provided with a removably secured base member 28 which is secured to the side walls 14 by means of bolts 30, and between the walls and base there is a gasket 32 which provides a water tight seal between side walls 14 and base 28. Container 12 is also provided with a top plate 34 which is removably secured to the side walls 14 of container 12 by means of bolts 36. The bolts 36 are electrically insulated from the side walls 14 and top plate 34 or are prepared from electrically insulating material. Two O-ring insulating seals 38 and 40 are employed to maintain a vacuum within crucible 16 and to electrically insulate the side walls 14 and the top plate 34. A vacuum and inert gas connection 42 is provided through which the crucible is evacuated by means of a vacuum pump (not shown) and then, if desired, filled with an inert or non-reactive gas atmosphere such, for example, as argon or helium.

The top plate 34 of container 12 is provided with a dynamic vacuum seal 44 through which passes electrode assembly 46. The electrode assembly 46 comprises a consumable electrode 48 of the material to be melted which is secured to electrode holder 50 of the electrode assembly. The electrode holder 50 of the electrode assembly is provided with a water inlet 52 and a water outlet 54 for the circulation of water through the hollow stems 56 and 58 for the purpose of cooling the electrode assembly 46.

A source of ultrasonic energy is removably supported in engagement with side walls 18 of crucible 16 and in such a position so as to transmit ultrasonic waves to molten metal as it is deposited from consumable electrode 48. The arrangement is such that the ultrasonic energy is transmitted with optimum efficiency throughout substantially the entire area of the melt during solidification thereof.

The source of sonic energy employed in this invention is preferably a magnetostrictive transducer unit 60 comprising a transducer stack 62 firmly connected in a low-loss joint as by silver brazing or by a carefully machined threaded connection to a wave transmittal coupling bar 64. The wave transmittal coupling bar 64 is adapted to make sliding engagement with interior surfaces of side walls 18 of crucible 16, and is secured thereto in any convenient manner as, for example, by means of a key and lock arrangement (not shown). An O-ring seal 65 is provided to maintain the interior of the crucible gas-tight.

As shown, the uppermost surface of the wave transmittal coupling bar 64 serves as the bottom closure 20 of the crucible 16. A suitable arrangement for providing convenient electrical connections to energizing coil 66 of the transducer unit 60 is provided, the form shown including a plug socket 68 connected to coil 66, said socket being set in the side wall of container 12.

It will be noted that the transducer unit 60 is positioned within the container 12 where it can be cooled by the same cooling means provided for cooling arc-melting crucible 16. As is well known in the art, transducer units may become quite hot in use and it is desirable to provide a means for cooling them during operation since heating said transducer above the Curie temperature of the transducer stack results in loss of the magnetostrictive characteristics which are required to generate the desired vibrations.

In utilizing the apparatus of this invention the arc is struck and controlled so that the initial deposit of molten metal forms a sound weld joint of substantial cross-sectional area with the bottom closure 20. The area of the weld joint should be as large as conveniently possible.

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Good results have been obtained with an area of as small as 20% of the total closure cross-sectional area but larger weld areas are more desirable. The weld joint must have ductility since brittle joints are easily fractured. A fractured joint is unsatisfactory because sonic energy will not be efficiently transmitted therethrough. If it is not practical to produce a satisfactory sound weld joint, then a suitable brazing alloy such, for example, as a high melting point silver solder may be employed to produce a sound brazed joint between the ingot and the bottom closure.

After a satisfactory joint has been formed, molten metal is continuously deposited from consumable electrode 48, and as the liquid or molten metal solidifies sonic energy is continuously delivered to the solid-liquid interface through the coupling bar and the contiguous solidified ingot from transducer unit 60. Vibrations of desired frequency and energy are transmitted from transducer stack 62 through coupling bar 64 and directly to the molten metal at the freezing solid-liquid interface. The solidified portion of the melt, owing to the weld or brazed joint that is produced becomes integral with the coupling bar and in effect provides a continuously lengthening wave transmittal coupling bar. Thus, the sonic energy is effectively and efficiently transmitted through the ever increasing length of transmittal bar to the freezing solid-liquid interface where the sonic energy is utilized to produce the desired improved grain structure in the resulting ingot. The sonic energy is thus provided with a path to the solid-liquid interface consisting essentially of metal in the solid state.

This invention is applicable also to the electron-beam type melting furnace such, for example, as that disclosed in Patent 2,809,905 to Davis et al., to electric arc furnaces of the permanent or non-consumable electrode type in which metal particles are continuously fed into an arc-melting crucible and the arc produced by means of the permanent electrode melts the powder, and to certain other melting furnaces employing induction heating. The initial portion of molten metal upon solidifying is controlled so as to provide a sound ductile joint with a wave transmittal coupling bar as described with reference to FIG. 1.

An embodiment of the invention, employing an arc furnace of the non-consumable electrode type is shown in FIG. 2 of the drawing. The basic furnace 70 of FIG. 2 is similar to that shown in FIG. 1 of the drawing. In FIG. 2 of the drawing a permanent electrode assembly 72 is shown which consists of a hollow stem of, for example, steel having brazed to the free end thereof a welding tip 74 of some high melting point material such, for example, as tungsten. The electrode assembly 72 is cooled in the same manner as a consumable electrode assembly 46 of FIG. 1 of the drawing. In order to supply finely divided metal or metal particles to the crucible of FIG. 2 of the drawing a hopper 76 is provided which has a conduit 78 leading to the melting crucible, and powdered metal 80 from such hopper may be introduced into the crucible continuously as by means of a screw type feed including a screw 82 driven by motor 84 through suitable reduction gearing 86, or the feed of the metal particles may be intermittent and controlled by a suitable hand operated means, as desired. Suitable means such as a conduit 88 may be provided for providing a vacuum or other inert atmosphere within hopper 80 so that the interior of the entire apparatus may be under the same conditions.

The furnace 70 comprises container 90 within which is disposed crucible or ingot mold 92. Crucible 92 is similar to that shown in FIG. 1 in that it comprises side walls 94 and bottom closure 96. Secured to the side walls 94 of crucible 92 is a transducer unit 98 comprising wave transmittal coupling bar 100 and transducer stack 102. The uppermost portion of coupling bar 100 serves as the bottom closure 96 of crucible 92.

The ultrasonic transducer unit 60 may be constructed to operate in frequencies in the sonic and ultrasonic range, and will be effective for the present invention at frequencies between about 1 kc. and 300 kc. per second. However, these frequencies are affected by certain practical considerations. Below about 15 kc., the waves produced by the transducer unit are audible to the human ear and may be objectionable. Likewise, in the higher wave lengths the shortening of the stack 62 or 102 makes it progressively more difficult to provide an energizing winding of sufficient size to generate the necessary energy; and with magnetostrictive transducers it has been found that about 50 kc. is the practical upper limit for some applications for this reason. Satisfactory results in producing ingots have been obtained by using frequencies in the range between about 10 kc. and 50 kc. With relatively small ingots; i.e., in which the wave length to ingot diameter (λ/D) is greater than unity, it has been found beneficial to vary the frequency to maintain the solid-liquid interface at a position of resonance. The transducer frequency may be held constant in treating larger ingots; i.e., those in which (λ/D) is equal to or less than unity, without sacrifice in efficiency.

For the purpose of this invention, it has been determined that the electrical energy input to the transducer required to produce the sound homogeneous ingots of desired grain structure on a practical basis should be at least 0.25 watt per square centimeter of interface between the molten metal and the solidified metal. The amount of electrical energy input required for substantial grain refinement over that normally obtained is related to the melting rate. A normal melting rate (built-up of ingot) is considered to be from $\frac{1}{8}$ inch to $\frac{3}{4}$ inch per minute. However, melting can be carried out at rates as low as .005 inch per minute, and as high as 3 or 4 inches per minute. The slower the solid-liquid interface moves, the smaller is the electrical energy input for ultrasonic vibration required to maintain a given degree of grain refinement. Thus, electrical energy inputs for ultrasonic vibration of less than 0.25 watt per square centimeter, for example 0.15 watt per square centimeter, can effect substantial grain refinement if the melting rate (build-up of ingot) is sufficiently slow, but for an energy input of less than 0.25 watt per square centimeter to be effective the required melting rate is so slow as to become impractical for most purposes. On the other hand, the faster the solid-liquid interface moves, the greater is the energy input required to maintain a given degree of grain refinement. Generally speaking, it is desired to use a relatively small energy input to the transducer, since this reduces the size of the ultrasonic components and the cost of the operation. The upper limit on rate of melting and energy input to the transducer, disregarding the cost factor, is imposed by the physical characteristics of the material being melted, for while undergoing sonic irradiation at high electrical energy inputs, the portion of the ingot which has lately solidified may fracture.

An experiment was conducted to determine the relative effectiveness of irradiating the solid-liquid interface, (1) through the solid, (2) through the liquid. The equipment used in the experiment was the zone-melting apparatus shown in FIG. 3. As indicated therein, a transducer 201 is integral with a coupling horn 202 and is welded or brazed at 203 to the ingot 206 of a type 316 stainless steel. The ingot 206 is supported by an aluminum oxide coated graphite boat 207. The ingot 206 and the graphite boat 207 are surrounded by the molybdenum susceptor 211 which rests on the magnesium oxide brick 208. Cylindrical furnace wall 212 of quartz supports the brick 208 and surrounds both the brick and the elements supported by it. An induction coil 213 surrounds the furnace wall and is movable longitudinally of the ingot to heat the ingot in a manner such that a narrow molten zone is formed which is movable longitudinally of the ingot either toward or away from the transducer.

It was discovered that moving the liquid zone towards the transducer; i.e., irradiating the freezing solid-liquid interface through the liquid, produced substantially no grain refinement. In contrast, moving the liquid zone away from the transducer; i.e., irradiating the freezing solid-liquid interface through the solid, produced marked grain refinement.

Example

An ingot 12 inches in cross-sectional diameter and 16 inches in length was prepared from a consumable electrode in apparatus similar to that shown in FIG. 1 of the drawing. The composition of the consumable electrode was, by weight, 0.25% carbon, 0.60% manganese, 0.015% phosphorus, 0.015% sulfur, 0.30% silicon, 2.7% nickel, 0.30% chromium, 0.50% molybdenum, 0.07% vanadium and the balance iron. The electrical energy input to the transducer was 1500 watts and the melting rate was $\frac{1}{4}$ inch per minute. Since the solid-liquid interface closely approaches a hemispherical shape in melting with the apparatus of FIG. 1, the energy input per square centimeter of interface was calculated for an interface of such shape and determined to be about 1 watt per square centimeter. The ingot had substantially small uniform equiaxed grain structure throughout, and was easily and readily hot worked. Ingots of the same composition prepared by prior art practices showed a long columnar grain structure and were difficult to hot work owing to the presence of planes of weakness.

A large number of metals and alloys may be melted and irradiated with sonic vibrations in similar fashion. Thus, for example, molybdenum ingots have been prepared as described with resulting improvement in grain structure.

Massive metal ingots prepared in accordance with this invention have shown certain marked improvements in metallurgical properties not heretofore obtainable in ingots of like size. Thus, for example, planes of weakness have been substantially eliminated and small insoluble particles are substantially uniformly dispersed throughout the ingot. The grain structure is greatly improved, being substantially smaller and equiaxed throughout the ingot.

It will be understood that the above illustrations and drawing are exemplary and not in limitation of the invention.

We claim as our invention:

1. An electric arc-melting furnace comprising an elongated crucible capable of containing a solidifying ingot, a melting electrode disposed in the crucible, said crucible comprising side walls and a bottom closure, means sealing the bottom closure to the side walls to provide a gas-tight seal, said bottom closure adapted to be welded to said solidifying ingot and an ultrasonic transducer unit comprising a wave transmitting coupling bar and a transducer stack attached by a low loss joint to the bar, the wave transmitting coupling bar of the transducer unit being integral with the bottom closure, whereby ultrasonic energy is directly transmitted through the said wave transmitting coupling bar to the bottom closure of the elongated crucible and thence directly to molten metal deposited on the bottom closure during operation of the arc-melting furnace.

2. An electric arc-melting furnace comprising a substantially gas-tight enclosure capable of containing a solidifying ingot, a cooled arc-melting crucible comprising side walls and a bottom closure, said bottom closure adapted to be partially melted and thereby welded to said solidifying ingot, means for sealing the bottom closure to the side walls, a consumable electrode extending downwardly into said crucible for supplying molten metal during operation of the furnace, means for providing an inert atmosphere within the gas-tight enclosure, and an ultrasonic transducer unit comprising a wave transmitting coupling bar and transducer stack attached by a low loss joint to the bar, the wave transmitting coupling bar of the transducer

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unit being integral with the bottom closure of the arc-melting crucible whereby ultrasonic energy is directly transmitted through the said wave transmitting coupling bar to the bottom closure and thence directly to molten metal deposited on the bottom closure during operation of the arc-melting furnace.

3. An electric arc-melting furnace comprising an elongated crucible capable of containing a solidifying ingot, a permanent electrode disposed in the crucible, means for supplying to said crucible metal to be melted by the electrode, said crucible comprising side walls and a bottom closure, said bottom closure adapted to be welded to said solidifying ingot, means sealing said bottom closure to the side walls to provide a gas-tight seal and an ultrasonic transducer unit comprising a wave transmitting coupling bar and a transducer stack attached to the bar by a low loss joint, the wave transmitting coupling bar of the transducer unit being integral with the bottom closure whereby ultrasonic energy is directly transmitted through the said wave transmitting coupling bar to the bottom closure and thence directly to molten metal deposited on the bottom closure during operation of the arc-melting furnace.

4. An electric arc-melting furnace comprising a substantially gas-tight enclosure capable of containing a solidifying ingot, a cooled arc-melting crucible, a permanent electrode extending downwardly into said crucible for melting metal during operation of the furnace, means for supplying metal particles to be melted to the interior of the crucible, means for providing an inert atmosphere within the gas-tight enclosure, and an ultrasonic transducer unit comprising a wave transmitting coupling bar and transducer stack attached by a low loss joint to the bar, the said arc-melting crucible comprising side walls and a bottom closure attached to the side walls, said bottom closure adapted to be partially melted and thereby welded to said solidifying ingot, means for sealing said bottom closure to said side walls to provide a gas-tight seal, the wave transmitting coupling bar of the transducer unit being integral with the bottom closure of the crucible whereby ultrasonic energy is directly transmitted through the said wave transmitting coupling bar to the bottom closure and thence directly to molten metal deposited on the bottom closure during operation of the arc-melting furnace.

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5. In a method of producing massive sound homogeneous metal ingots, the steps comprising arc-melting a metal out of contact with a reactive gas, depositing the arc-melted metal in successive relatively thin increments upon a crucible base so as to melt a portion of the base and thereby form a sound weld joint of substantial area between the ingot and base, applying sonic energy having a frequency in the range from 10 kc. to 50 kc. directly to the crucible base whereby sonic energy is transmitted to the freezing solid-liquid interface through a path consisting essentially entirely of metal in the solid state to provide for effective and efficient vibration of the molten metal at the interface during solidification thereof.

6. In an arc-melting method of producing massive sound homogeneous metal ingots having substantially equiaxed grain structure throughout, the steps comprising arc-melting a metal out of contact with a reactive gas, depositing the arc-melted metal upon a crucible base so as to form a sound weld joint having a cross-sectional area at least 20% that of the base between the ingot and the crucible base, and as the metal is continuously deposited applying sonic energy directly to the crucible base at a frequency of from about 10 kc. to 50 kc. per second and in an amount of at least .25 watt per square centimeter of interface between the molten metal being deposited and the solidified portion of the melt.

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