

Dec. 13, 1960

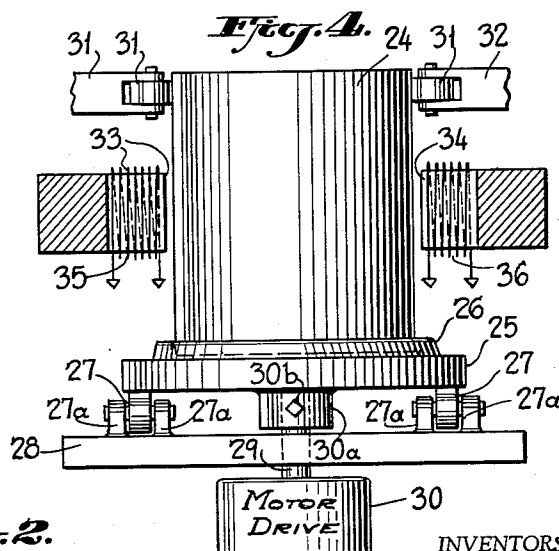
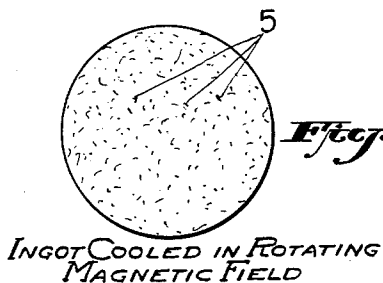
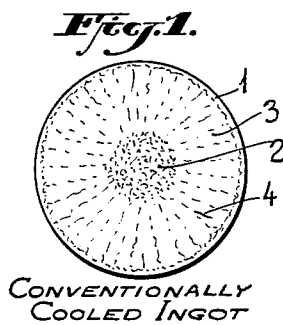
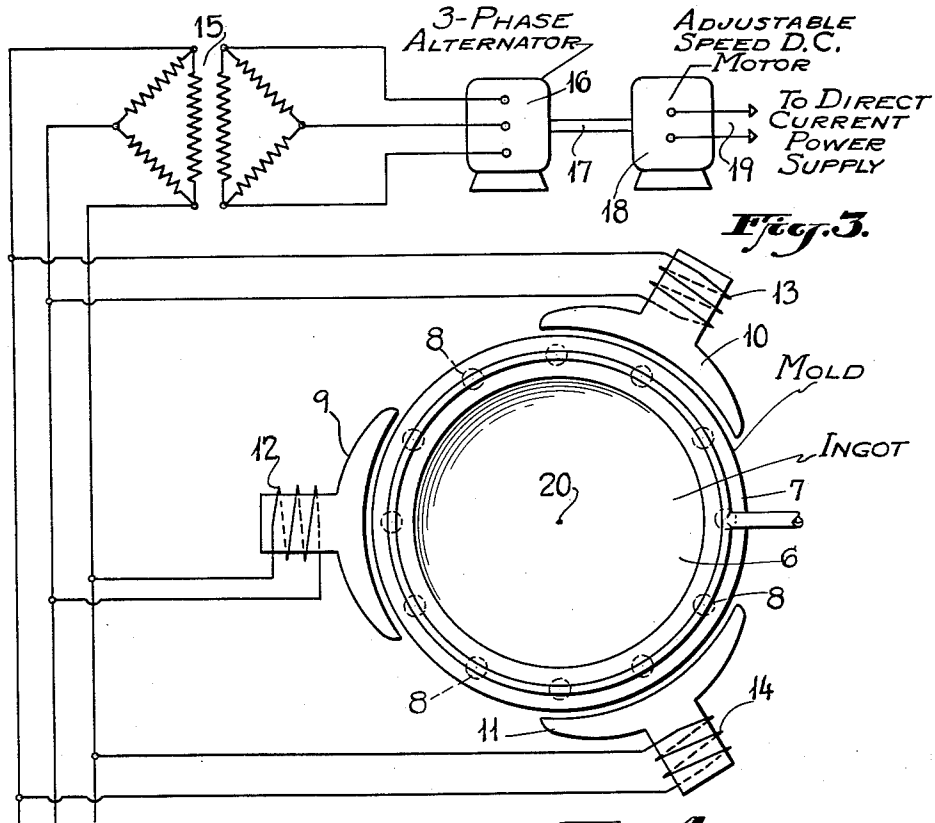
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2,963,758

PRODUCTION OF FINE GRAINED METAL CASTINGS

Filed June 27, 1958

8 Sheets-Sheet 1



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Fig. 5.

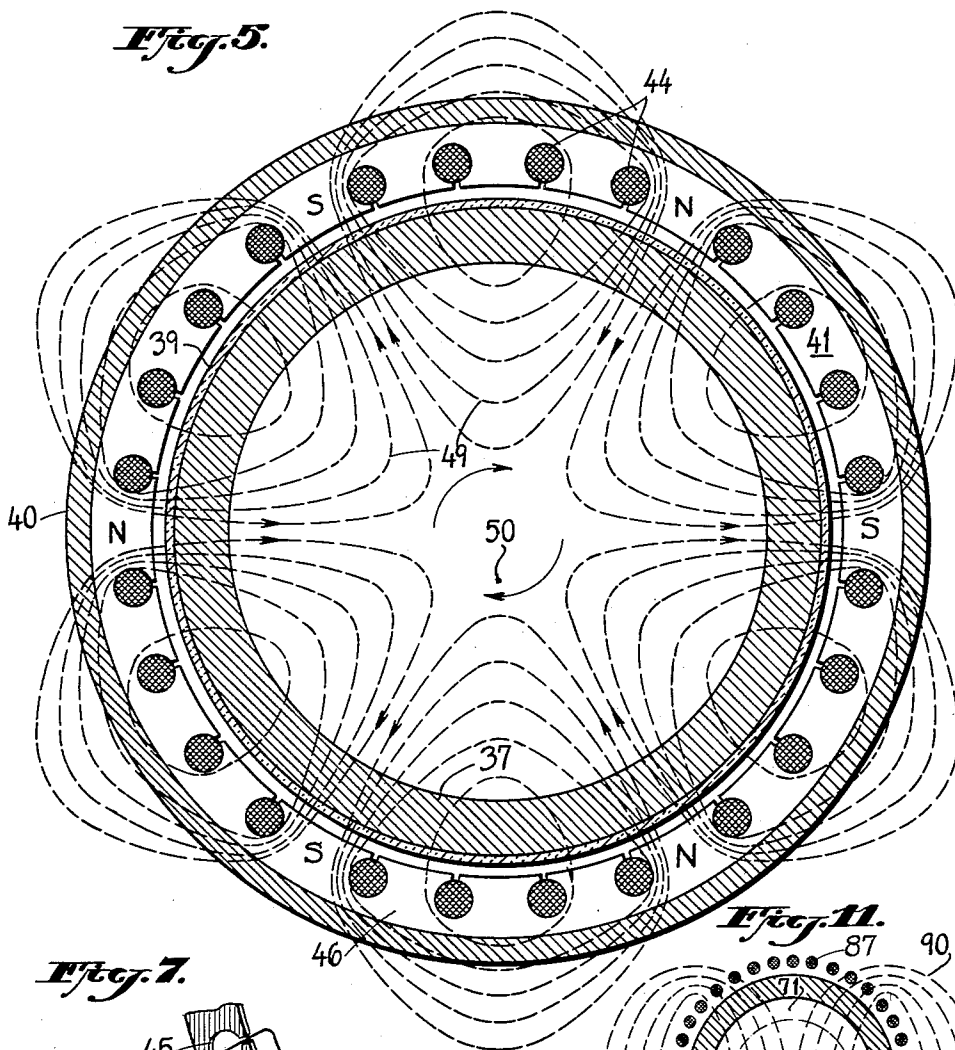


Fig. 7.

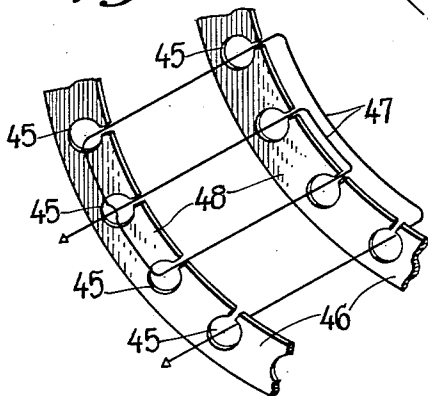
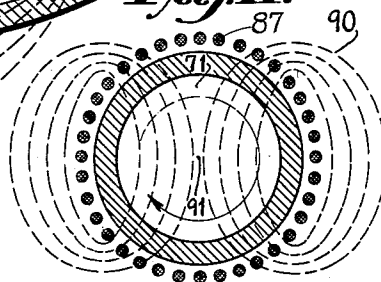


Fig. 11.



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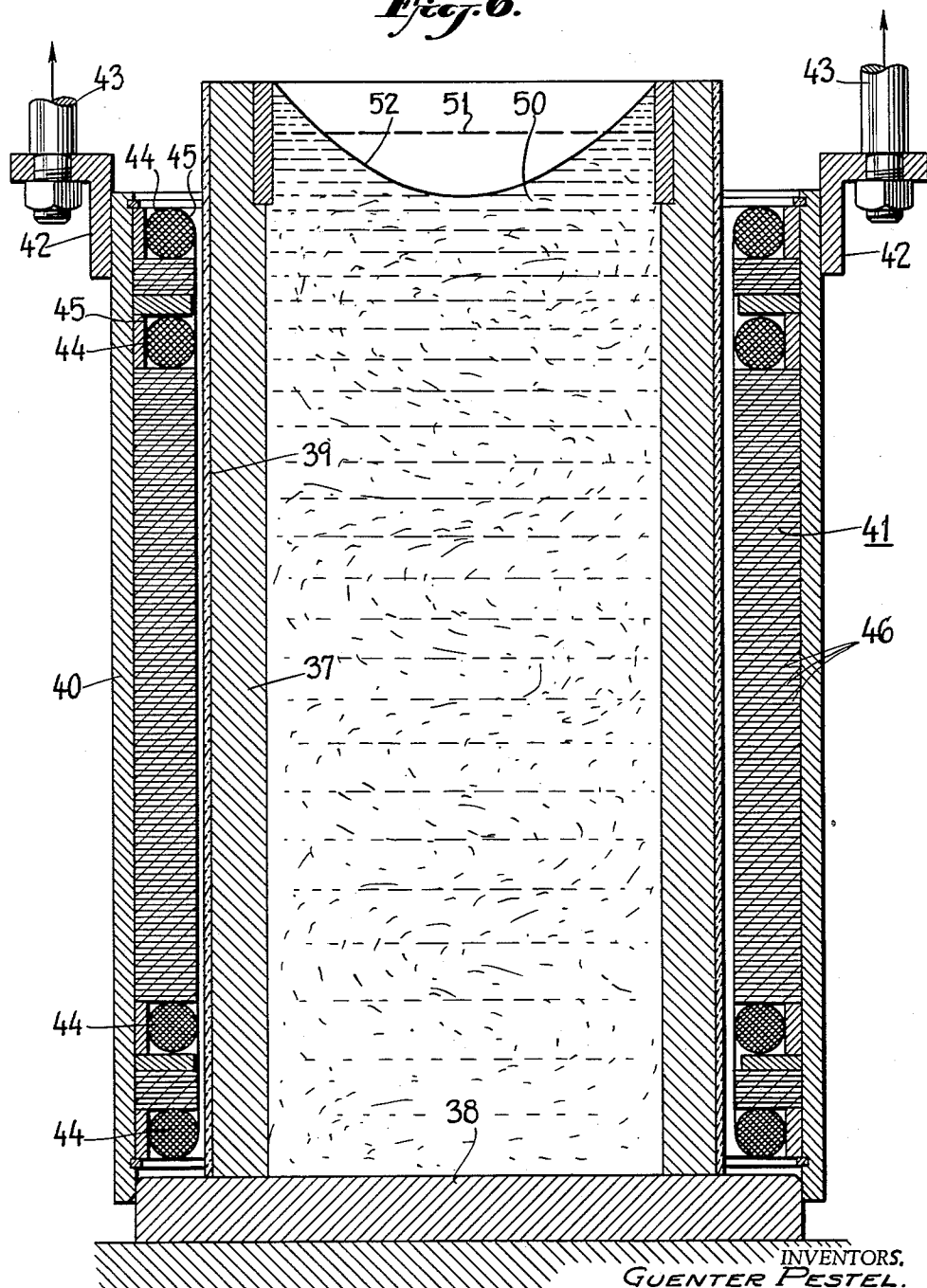
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Fig. 6.



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PRODUCTION OF FINE GRAINED METAL CASTINGS

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Fig. 8.

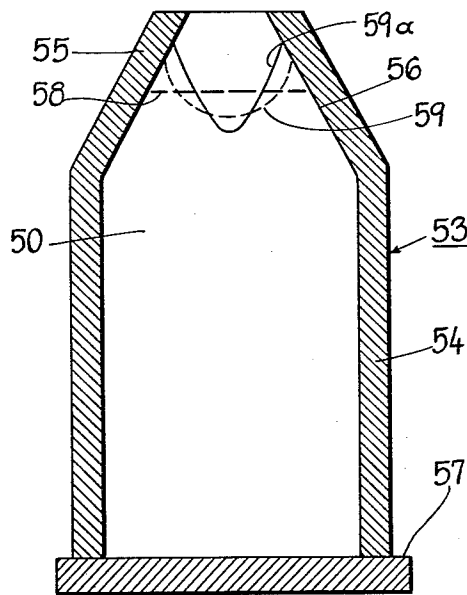
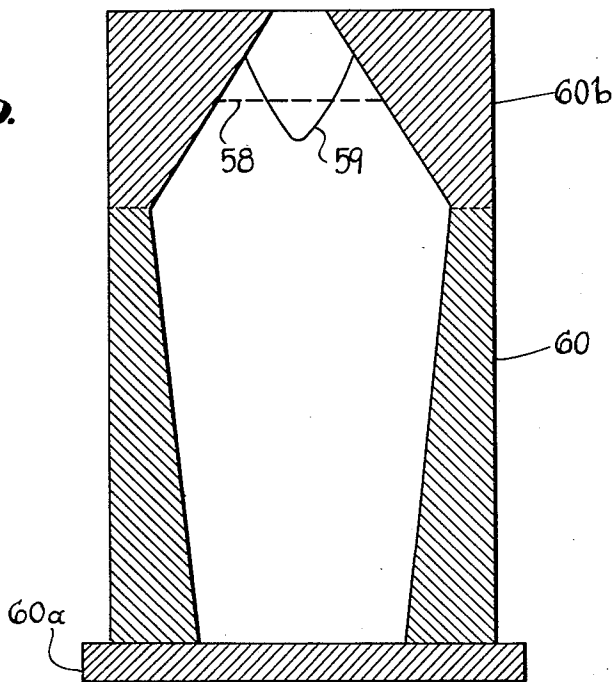


Fig. 9.



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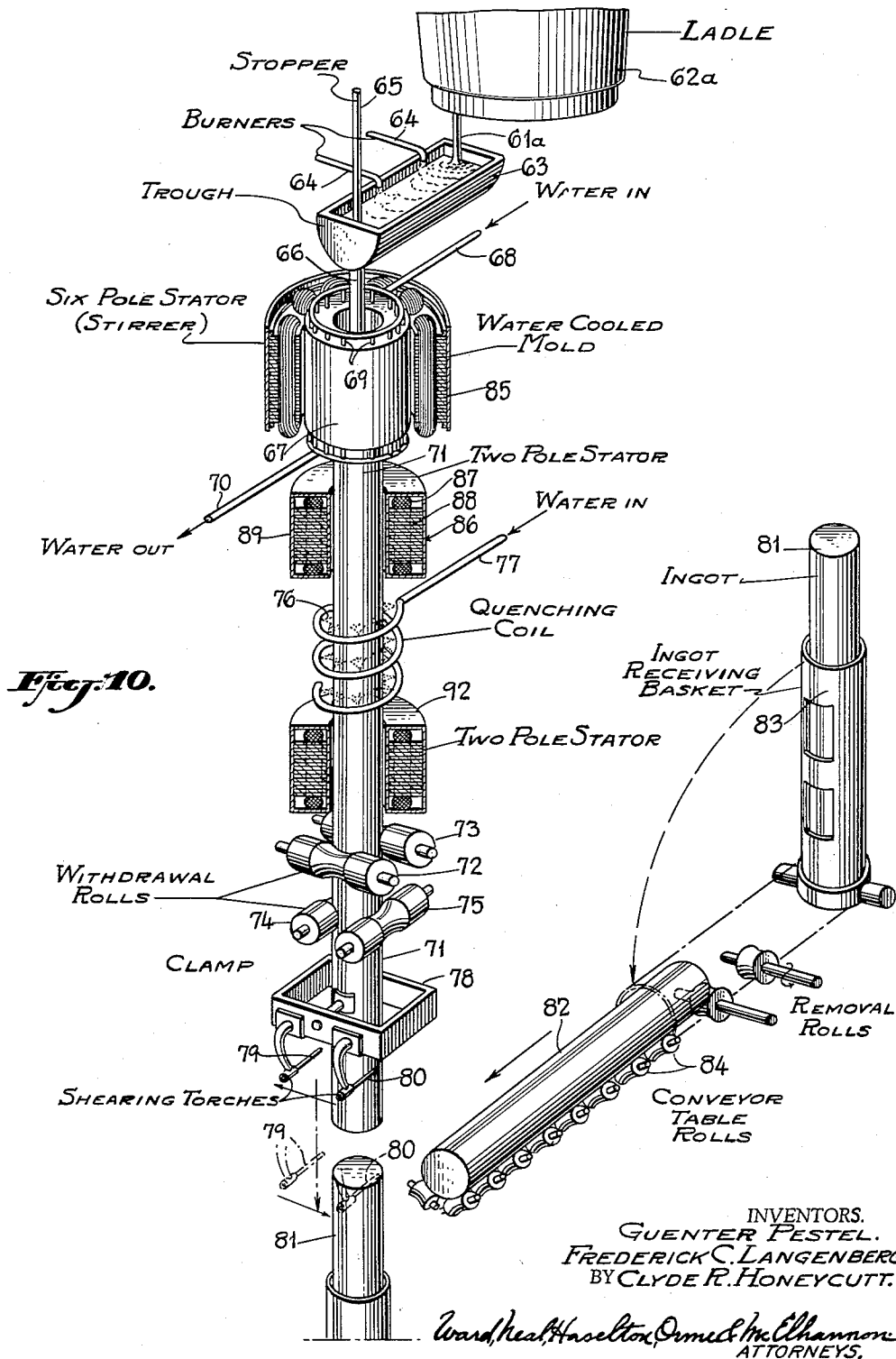
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Fig.12

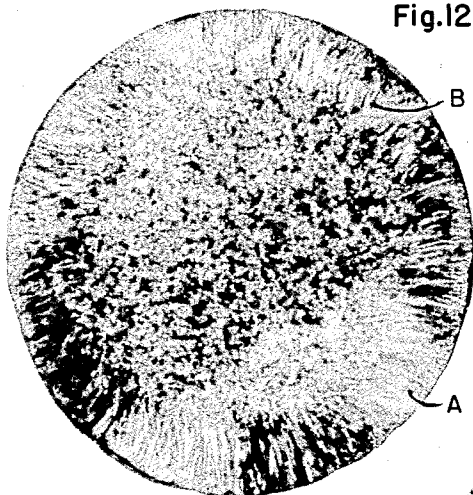


Fig.13

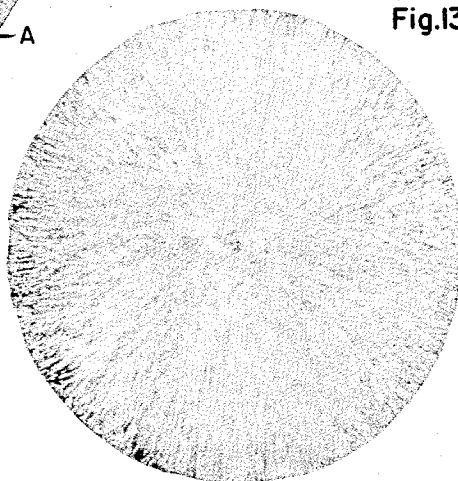
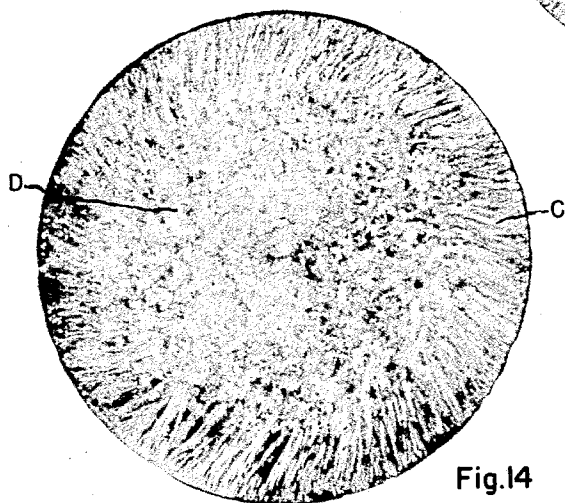


Fig.14



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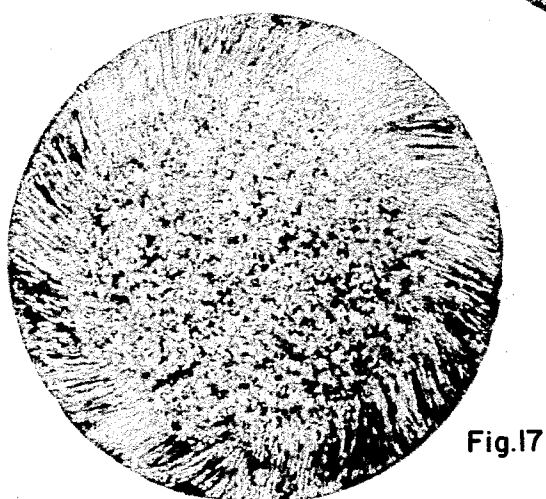
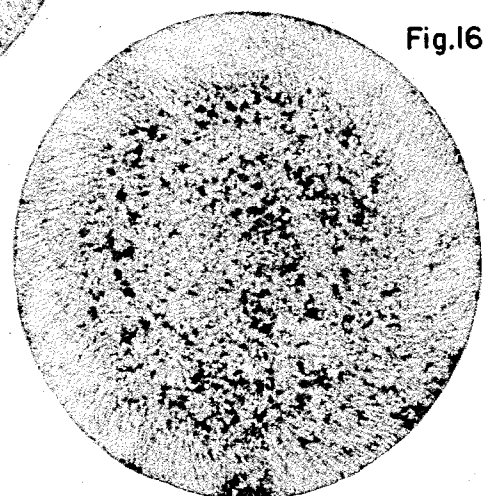
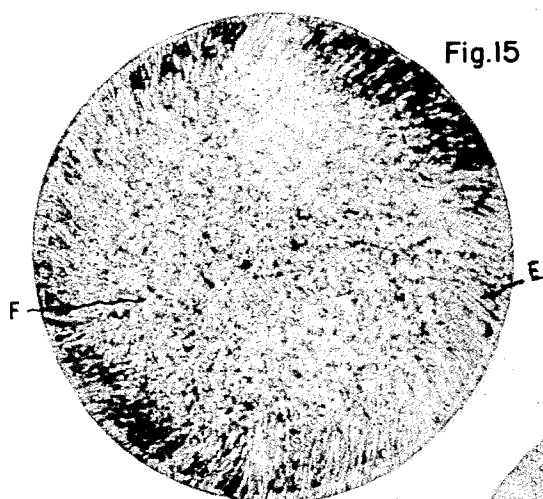
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PRODUCTION OF FINE GRAINED METAL CASTINGS

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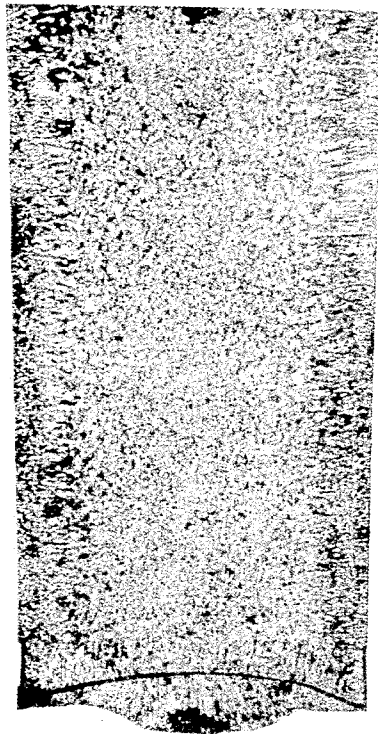
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PRODUCTION OF FINE GRAINED METAL CASTINGS

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Fig.18



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PRODUCTION OF FINE GRAINED METAL CASTINGS

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Filed June 27, 1958, Ser. No. 745,791

6 Claims. (Cl. 22-216)

This invention relates to methods and apparatus for controlling grain growth in metals on cooling and solidifying from the molten state, and more particularly to the application of such methods and apparatus for refining the grain of alloy steels and other metals which tend to form relatively large grains on solidifying from a molten condition.

This application is a continuation-in-part of our co-pending application Serial No. 668,189, filed June 26, 1957, now abandoned, and assigned to the assignee of the present application.

When molten metal contacts the wall of a mold, solidification begins almost instantaneously adjacent the wall of the mold due to the chilling action of the mold wall. In this initial solidification or chill zone, a large number of crystal nuclei are formed which result in a layer of randomly oriented small crystals. Since most of the heat of the molten mass is extracted through the surface of the mass, a temperature gradient is established in the mass which is approximately at right angles to the metal-mold interface. Subsequent solidification of the metal takes place in the direction of the thermal gradient, and starting from the inner surface of the thin outer layer of randomly oriented crystals or grains, columnar crystals begin to grow with their axes nearly perpendicular to the surface of the mold wall, or more accurately, perpendicular to the isothermals in the liquid metal. The temperature gradient becomes less near the center of the molten mass, and at some point intermediate the outer solid layer and the center of the mass, the temperature gradient may be insufficient to continue a columnar growth. At this point fresh nuclei form ahead of the solid-liquid interface, and equi-axed crystals of random orientation form in the remaining metal.

The size of the columnar grains depends upon many factors, such as the casting temperature of the molten metal, the rate of teeming, the temperature, thickness and physical properties of the mold, the mold coating, the size of the ingot, the degree of turbulence, the gas content of the metal and the amount of convection current in the molten metal. Also, the size of the grains is affected by the composition of the metal since the composition affects the range of temperature change required for solidification.

The invention is useful principally in the treatment of metals in which relatively large columnar grains are formed during cooling, and therefore, the invention is applicable to the treatment of almost all alloy steels. Although the gas evolution during the casting of rimmed-steel ingots is so great that the columnar grain zone does not form, almost all killed or semi-killed steel ingots show a chill zone, a columnar zone and central zone.

The formation of large columnar grains, known as "ingotism," is harmful in the further fabrication of the ingot. For example, large columnar grains increase the likelihood that the ingot will tear in subsequent shaping or working processes, such as forging or rolling. Also, cleavage planes or lines of weakness, may be formed

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at the intersections of columnar grains, which grow from different directions, and such cleavage planes are the causes of cracks in the metal during rolling.

We have discovered that if molten metal, such as steel, is magnetically stirred within a non-magnetic mold and in a particular manner during cooling, the resulting casting or ingot has a refined grain structure and the formation of large columnar grains is prevented. In the preferred form of the invention, the molten metal is stirred electro-magnetically in a direction extending transversely to the direction in which the columnar grains tend to form. The molten metal is stirred by an electro-magnetic field which rotates about the entire length of an axis extending longitudinally and through the center of the molten mass. Previous attempts to refine the grain of steel by the use of magnetic fields have indicated that the magnetic field should be applied only after the ingot has partially solidified. We have found, to the contrary, that the magnetic field should be applied as soon as the liquid metal enters the mold in order that grain refinement can be achieved in the peripheral portions of the ingot. Otherwise, the initial cooling period will produce columnar grains extending perpendicular to the mold wall such that portions of cleavage planes are still formed in the ingot. We have found further that in order to obtain optimum results, the field intensity of the magnetic field must be within a predetermined range defined by a design constant and that the field intensity must be reduced in the latter stages of solidification in order to prevent the formation of center porosity in the mold.

Accordingly, it is a primary object of our invention to provide a new and improved method for preventing the growth of columnar crystals in a cooled ingot by means of a rotating magnetic field.

More specifically, an object of our invention is to provide an arrangement wherein molten steel is solidified within a non-magnetic mold under the influence of a rotating magnetic field. As will become apparent from the following description, we have found that by using a non-magnetic mold, grain refinement will occur at a particular field intensity strength; whereas, if a magnetic mold were used, substantially no refinement would occur at the same intensity.

Another object of our invention is to provide a method for grain refinement wherein a magnetic field surrounds the entirety of an ingot mold rather than merely a portion thereof to achieve a uniform grain structure throughout the entire length of the mold.

A further object of our invention lies in the provision of a method for grain refinement wherein a rotating magnetic field is applied while molten metal is being initially poured into a mold to impede any formation of columnar crystals at the edges of the ingot.

Another object of our invention is to provide a method for ingot grain refinement wherein the field intensity of a rotating magnetic field is controlled within predetermined limits to obtain maximum grain refinement.

Still another object of our invention is to provide a new and improved method for continuous casting molten metal while producing a fine-grained structure in the cast product.

Other objects and advantages of the invention will be apparent from the following detailed description of the manner in which we prefer to practice the invention, which description should be considered in conjunction with the accompanying drawings in which:

Figure 1 is a diagram which illustrates, in transverse section, the grain growth in ingots which have been cast in accordance with conventional casting technique;

Fig. 2 is a diagram which illustrates the grain structure of ingots which have been solidified from the molten state in accordance with the present invention;

Fig. 3 is a schematic diagram illustrating an apparatus for producing a rotating electro-magnetic field and accompanying rotative stirring in molten metal within a mold;

Fig. 4 illustrates schematically an alternative arrangement for rotatively stirring molten metal within a mold by means of a stationary electro-magnetic field;

Figs. 5 and 6 are, respectively, views in plan and longitudinal sectional elevation of a preferred form of apparatus of the invention;

Fig. 7 is a fragmentary, schematic view of a portion of the apparatus shown in Figs. 5 and 6;

Figs. 8 and 9 are views in longitudinal axial sectional elevation of preferred forms of mold for use in practicing the invention;

Fig. 10 is a schematic drawing illustrating the application of the invention to the continuous casting of steel ingots;

Fig. 11 is a schematic diagram which illustrates the magnetic field produced by a portion of the apparatus shown in Fig. 10; and

Figs. 12-18 are photographs of the cross sections of various ingots showing the effect on grain structure of rotating magnetic fields of various strengths.

Fig. 1, which is a diagrammatic showing of the cross-section of a typical cylindrical steel ingot cooled in a conventional manner under static conditions, illustrates the grain formation in such an ingot. Thus, the ingot has a relatively thin outer solidification or chill zone 1 having a relatively fine, randomly oriented grain structure, a central zone 2 also of equi-axed, randomly oriented grain structure and an intermediate zone 3 having relatively coarse grain structure and comprising a plurality of relatively coarse, radially oriented, or columnar, grains 4.

Fig. 2 illustrates diagrammatically the grain structure of an ingot which has been cooled and solidified in a rotating magnetic field in accordance with this invention. In this figure, it will be noted that the grains 5 are all relatively fine and are randomly oriented.

The apparatus shown in Fig. 3 is not the preferred form of the invention and is included herein, because of its simplicity, to illustrate the concept of the invention. In Figure 3 molten metal 6 is contained in a mold 7 which may be cooled by circulation of water or other coolant through tubes 8 in the wall of the mold. The mold is constructed of non-magnetic material and may, for example, be constructed of austenitic cast iron, austenitic stainless steel, ceramic, etc., or a combination of such materials. In addition, because of the temperatures encountered during the casting and solidification of the metal, the mold may be formed at least in part from a steel which is magnetic at room temperatures, but which is non-magnetic at the elevated operating temperatures. It has been found that if a ferromagnetic mold is used, a strong magnetic field is produced just inside the wall of the mold; however, the field decreases very rapidly in the region near the mold walls; and the stirring effect in the molten metal is very poor. Consequently, it is vitally important that non-ferromagnetic material be used for the mold.

For the purpose of developing a rotating magnetic field within the molten mass of metal 6, three pole pieces, 9, 10 and 11 of magnetic material, having energizing windings 12, 13 and 14 are disposed around the mold 7 at angular spacings of 120° each. The windings 12-14, inclusive, are respectively connected in a conventional manner to the successive phases of a three-phase transformer 15 whose input is connected to a three-phase power source, such as a three-phase alternator 16 which may be driven via a shaft 17 from a direct current motor 18 energized over input leads 19 from a suitable direct current power supply. The motor 16 is preferably adjustable in speed by conventional means for adjusting the output frequency and voltage of the alternator 16, for purposes explained below.

As is well known in the art, the pole pieces 9-11 and the windings 12-14 thereon, the latter when connected as described above, will produce a rotating magnetic field in the conductive molten metal 6. When a magnetic field is moved with respect to a conducting material, electrical currents are induced in the material, and the induced currents create a secondary magnetic field of such polarity that the inducing and induced fields interact and produce a force which tends to move the conducting material in the same direction that the inducing field is moving. The force exerted on the conducting material is directly proportional to the square of the flux density of the primary or inducing field and is inversely proportional to the resistivity of the conducting material. Accordingly, the molten metal 6 will be caused to rotate around the vertical axis 20 thereof, by the rotating magnetic field aforesaid, and the speed of rotation will depend not only upon the flux density and the resistivity of the molten metal, but also upon the frequency of the energy supplied to the windings 12-14, inclusive, from the alternator 16. Such rotation of the metal causes stirring of the metal and controls the grain growth during cooling as described hereinafter.

Stirring of the molten metal should commence as soon as the metal starts to cool, and therefore, in the embodiment shown in Fig. 3, the windings 12-14 should be energized while the metal is being poured into the mold 7 or shortly thereafter. On the other hand, if means are provided for heating the mold 7 and for maintaining the metal in a molten state within the mold 7, it is not necessary to energize the windings 12-14 until cooling of the metal is commenced.

The necessity of energizing the windings when the metal is initially poured into the mold is vividly illustrated in Figure 12, which is a photograph of the etched cross-section of a type 310 stainless steel ingot in which the power was applied 10 seconds after the metal filled the mold. It will be noted that the initial solidification at A is perpendicular to the mold wall and bending occurs at B only when the field is applied. The columnar grains at A are those which produce cleavage planes in the ingot; and, thus, since the power was not applied at the beginning of the pouring, the ingot has an inherent weakness and may fracture during fabrication.

At increased distances from the interior wall of the mold 7, the molten metal will be rotated by the magnetic field with proportionally larger angular velocities because of the viscosity of the metal which varies with distance from the interior wall of the mold 7, the metal near the wall being more viscous than the metal near center 20. The variation in angular velocity in the radial direction prevents the formation of columnar crystals since the growing tip of each columnar crystal is sheared off by the faster moving metal nearer the center of the mass.

The velocity of rotation of the molten metal may be controlled by controlling the frequency and/or voltage impressed on the windings 12-14, and the greater the velocity of rotation of the molten metal, the greater will be the difference in speed of adjacent particles. Hence, the fineness of the grain of the resulting ingot may be controlled by appropriately controlling the energization of the windings 12-14 in the manner aforesaid during cooling and progressive solidification of the metal. On the other hand, the upper surface of a rotating fluid assumes a concave parabolic shape in order to balance centrifugal and centripetal forces, and at excessive rotational speeds the metal will tend to overflow the mold 7 if of conventional design. We have found that there is a range of field intensities within which optimum grain refinement occurs. For iron-base alloys this range is best described by the design constant:

$$WH^2a^2=K=\text{constant}$$

W=rate of rotation of the magnetization vector within an element of metal near the liquid solid interface;

H =magnetic field intensity in oersteds; and
 a =radius from the mold or ingot center to the point at which columnar grain growth begins during solidification of the ingot. The value of a may be determined for a specific metal composition by casting an ingot thereof in the absence of a magnetic field, transversely sectioning and thereafter etching the ingot in any suitable manner as well known to the art, and measuring the length a . For molds other than those of a right cylindrical form, the value of a is, of course, the mean value determined by measuring a number of spaced apart sections.

It has been determined by experiment that for optimum grain refinement, the quantity K should be in the range of

$$10^9 \text{ to } 10^{10} \frac{\text{oersteds}^2 \text{ cms.}^2}{\text{second}}$$

and preferably in the range of

$$2.0 \times 10^9 \text{ to } 4.8 \times 10^9 \frac{\text{oersteds}^2 \text{ cms.}^2}{\text{second}}$$

Thus, since a can be easily determined and since W can be determined from the frequency of the current supplied to the windings 12-14, the required current which determines H , may be calculated. The foregoing constant applies as solidification progresses near the outer areas of the ingot. As solidification approaches the center of the ingot, however, the applied current should be reduced to about one-half of its original value. Otherwise, the center of the ingot could tend to be slightly porous because of improper feeding.

The effect of various power inputs is shown in the cross-sectional photographs of Figs. 13-17. In each case, the steel cast was type 310 stainless. Fig. 13 illustrates the columnar grain growth produced in an ingot which was cooled with no magnetic field applied. It will be noted that the needle-like grains extend from the center of the ingot all the way to the chill zone at the outer periphery. Figure 14 illustrates the grain structure when the aforesaid constant, K , is

$$1.00 \times 10^9 \frac{\text{oer.}^2 \text{ cm.}^2}{\text{sec.}}$$

Here it is seen that the initial growth of the grains at C is bent in the direction of movement of the rotating magnetic field. At D the columnar grain growth stops, and the remainder of the ingot is fine-grained. In Fig. 15, K is equal to

$$2.34 \times 10^9 \frac{\text{oer.}^2 \text{ cm.}^2}{\text{sec.}}$$

The initial grain growth at E is bent further in the direction of movement of the magnetic field and the area of fine grains at F is greater than in Fig. 14. In Fig. 16, the columnar growth has almost disappeared with K being equal to

$$4.30 \times 10^9 \frac{\text{oer.}^2 \text{ cm.}^2}{\text{sec.}}$$

and substantially the entire cross-section is fine-grained. However, when the factor K is increased further as in Fig. 17 where it is

$$7.36 \times 10^9 \frac{\text{oer.}^2 \text{ cm.}^2}{\text{sec.}}$$

the coarse grains at the edges again appear (although bent at considerable angles to the radii), probably due to the increased turbulence caused by the intensified field. Thus, the factor K should be between

$$10^9 \text{ and } 10^{10} \frac{\text{oer.}^2 \text{ cm.}^2}{\text{sec.}}$$

and preferably between

$$2.0 \text{ and } 10^9 \text{ and } 4.8 \times 10^9 \frac{\text{oer.}^2 \text{ cm.}^2}{\text{sec.}}$$

- It should be understood that the values of K given above apply only to iron base alloys since the resistivities of other metals and alloys in the molten state differ from that of iron. It may be said, however, that the constant for any metal or alloy, K^1 , is related to the constant K for iron base alloys by the equation:

$$K^1 = K(R)$$

- where R is the ratio of electrical resistivity of any molten metal or alloy under consideration over that of molten iron. Thus,

$$K^1 = WH^2 a^2 (R)$$

where the symbols correspond to those given above.

- Because the mold and its contents are relatively heavy, it is desirable to rotate the magnetic field rather than the mold and its contents. However, it is easier to produce relatively strong magnetic fields by employing direct current energization of the field producing means, and therefore, if desired, the apparatus illustrated schematically in Fig. 4 may be employed in place of the apparatus illustrated in Fig. 3. In Fig. 4 the mold 24 is mounted on a rotatable table 25, the mold 24 being held in place on the table by a ring 26 secured to the table. The table 25 is rotatably supported by rollers 27 journaled to bearing studs 27a integral with a base plate 28. A shaft 29 driven by a motor 30 extends through a central bore in the base plate 28 and thence into a bore of a boss 30a integral with the underside of the table 25. The shaft 29 is detachably secured to the boss 30a by means of a bolt 30b threaded through the boss and bearing against the shaft. Rotation of the motor 30 thus rotates the table 25 and mold 24 mounted thereon.

- The upper end of the mold 24 is steadied by rollers 31 bearing against the sides of the mold 24 and journaled to fixed arms 32. A uni-directional magnetic field extending into the metal within the mold 24 and transversely to the longitudinal axis thereof is produced by a pair of magnetic pole pieces 33 and 34 having windings 35 and 36 which may be energized from any conventional direct current source (not shown). Although only two poles have been illustrated in Fig. 4, it will be understood that a greater number may be employed.

- During operation of the apparatus illustrated in Fig. 4, the pole pieces 33, 34 and hence the magnetic field produced thereby, remain stationary, whereas the mold 24 and the metal contained therein are rotated during the cooling of the molten metal within the mold. Thus, the interaction between the stationary magnetic field and the rotating bath of molten metal provides a braking action which tends to reduce the speed of rotation of the molten metal as compared to that of the mold. Accordingly, grain refinement during solidification is effected in basically the same manner as in the Fig. 3 modification, i.e., by relative motion at the interface between the solidifying and still molten portions of the bath, as the bath solidifies progressively from its outer peripheral surface towards its central axis of rotation.

- The preferred embodiment of our invention is shown in Figs. 5 and 6. An annular mold 37 rests on a base plate 38 within an annular metal housing 40, within which there is also mounted and disposed in spaced relation to the mold, an annular stator structure shown generally at 41 which extends along the entire length of the mold. The upper portion of the housing 40 has welded or otherwise secured thereto, brackets, as at 42, which are drilled for reception of bolts, 43, which latter extend to fixed supports, not shown, to prevent swaying of the assembly during the casting and subsequent solidification of the molten metal in the rotating magnetic field.

- The mold 37 and base plate 38 are preferably made of non-magnetic material such as a ceramic refractory

or a non-magnetic metal such as austenitic cast iron or steel. The annular mold element 37 is preferably provided with an outer sheath 39 of asbestos or other suitable thermal insulating material for minimizing heat transfer from the mold cavity to the exterior.

The stator structure 41 for providing the rotating magnetic field is similar to the stator of a three-phase, six-pole induction motor of conventional design, the energizing coils of which, as at 44, are housed in slots, as at 45, of a laminated core 46 of magnetic material, such as iron of high permeability. The mode of winding, arrangement of the coils in the core slots, and mode of interconnection of the coils for providing a stator of the aforesaid six-pole, three-phase design is of course conventional and hence requires no detailed description. The winding may be of the progressive "lap" type or of the "concentric" type, the latter as shown schematically for one of the coils, as at 47 in Fig. 7, this view also showing at 48 a fragmentary portion of one of the slotted laminations of which the core 46 is composed.

The successive phases of the stator winding are respectively connected to the successive phases of a three-phase A.C. supply, in the manner described above with respect to Fig. 3, and will thus provide a rotating magnetic field, the magnetic flux distribution of which will, at any given instant, be distributed about as shown at 49 of Fig. 5. This magnetic field will form alternate north and south poles, as indicated at N and S in the drawings, it being understood that the field thus established rotates continuously at a uniform angular speed determined by the frequency of the A.C. power supply.

As a result, the bath of molten metal 50 within the mold will be rotatively stirred during cooling, and the effect on grain growth during progressive cooling and solidification of the metal, will be similar to that described above with reference to Fig. 3. However, by the employment of a number of field poles greater than the two-pole arrangement of Fig. 3, a lower rotative speed of stirring is obtained for a given frequency of alternating current energization in accordance with the equation:

$$R=120\frac{f}{p}$$

wherein R equals the rotative speed of the magnetic field in revolutions per minute; f is the frequency in cycles per second of the alternating current power supply; and p is the number of magnetic poles formed by the stator. Other distinctions between the six-pole stator arrangement of Fig. 5 as compared to the two-pole stator arrangement of Fig. 3 as regards effect on magnetic stirring will be discussed below.

Referring to Fig. 6, during rotative stirring of the molten metal bath 50, the centrifuging action will cause the upper surface to be displaced from its static level, indicated at 51, and caused to assume the parabolic contour indicated at 52, wherein the outer peripheral portions are displaced above the static level in accordance with well known principles. The total height of this parabolic surface of course increases with the rotative speed of the molten metal for any given internal diameter of the mold, and also increases with the internal mold diameter for any given rotative speed of stirring in accordance with the equation:

$$H=KW^2\left(\frac{D}{2}\right)^2$$

wherein H is the height of the parabolic surface from the center of the mold to its inner wall; K is a constant; W is the angular speed of rotative stirring; and D is the inner diameter of the mold.

Since the conventional type of mold shown in Fig. 6 has a relatively large and uniform internal diameter, the molten metal thus tends to rise along the inner wall of the mold to overflow the mold at a relatively low rota-

tive speed of stirring. This difficulty is overcome to a considerable extent with the modified mold constructions of Figs. 8 and 9 according to one aspect of the present invention.

It is important to note that in Fig. 6 the core 46 surrounds the entirety of the mold. Without this arrangement, non-uniform grain refinement occurs. In Fig. 18 the longitudinal cross section of an ingot of 310 stainless steel is shown in which the field surrounded the lower portion of the mold only. With this arrangement, fine grains are formed in the area surrounded by the field; however, in the upper portion where the field was not applied, coarse grains are formed. Therefore, in order to obtain a homogeneous grain refinement throughout the entirety of the ingot, it is vitally important that the field surround the ingot along the entire length of its axis as shown in Figures 5 and 6.

Referring to Figure 8, the mold proper, designated generally at 53, comprises a lower portion 54 of uniform internal diameter, and an upper portion 55 of progressively decreasing internal diameter as at 56, in passing from the base of the top thereof. The mold rests on a separate base plate 57 and the solidified ingot is discharged from the base of the mold proper 53, by lifting it off the base.

If now the mold of Fig. 8 is initially filled with molten metal to a static level shown at 58, the centrifuging action due to rotative stirring will impart to the upper surface of the molten metal a parabolic contour, as at 59, which at any given speed of rotative stirring, will have a depth much less than in the case of the mold construction of Fig. 6, owing to the much smaller internal diameter of the portion of the mold wall which is contacted by the upper surface of the molten metal in Fig. 8 as compared to the Fig. 6 embodiment. Furthermore, with the Fig. 8 embodiment as the speed of rotative stirring is further increased thereby increasing the depth of the parabolic surface as at 59a, the diameter at which the molten metal contacts the inner wall of the mold is correspondingly decreased owing to the converging throat of the mold, thereby minimizing the tendency of the molten metal to creep up the inner wall of the mold and overflow the top with increase in speed of rotative stirring.

In the mold construction of Fig. 9, the same principles are involved as in Fig. 8, except that in Fig. 9, the mold comprises a lower portion 60, of decreasing internal diameter from top to bottom, this portion resting on a base 60a and being surmounted by a removable top 60b, the internal diameter of which progressively decreases bottom to top. In this construction, upon solidification of the ingot the top 60b is lifted off, and the ingot discharged by upending the lower portion 60 of the mold. Assuming the mold to be filled with molten metal to the static level indicated at 58, the centrifuging action during rotative stirring will be the same as in the Fig. 8 modification, as evidenced by the upper parabolic surface 59 imparted to the molten metal during such stirring.

The invention is particularly applicable in one of its aspects to the continuous casting of metals, and Fig. 10 illustrates schematically one form of continuous casting apparatus having electromagnetic stirring devices in accordance with the invention, embodied therein. Molten metal 61a flows from a ladle 62a into a trough 63. When the stopper 65 is removed from the outlet of the trough 63, the molten metal 66 flows into a water-cooled mold 67, water being circulated through the mold 67 by means of the conduits 68, 69 and 70. A peripheral portion of the molten metal in the mold, adjacent the interior wall of the mold 67, solidifies within the mold 67 progressively and continuously forming a cylindrical ingot 71 having a molten core. The ingot 71 is fed downwardly by means of the motor driven withdrawal rolls 72-75, and the ingot 71 as it passes out of the mold 67, is further cooled by means of a water spray 76 ejected from a suitably perforated pipe 77 which encircles

the ingot 71. The ingot 71 moves continuously in the downward direction and by the time each portion thereof reaches the withdrawal rolls 72 and 73, the ingot 71 is substantially solid throughout.

From the withdrawal rolls 74 and 75, the ingot 71 passes through a carriage 78 which intermittently grips the ingot 71 and which carries a pair of shearing torches 79 and 80. The torches 79 and 80 cut the ingot 71 into sections 81 and 82 of the desired length as the carriage 78 moves downwardly with the ingot 71. The section 81 drops into an ingot receiving basket 83 which transfers the sections to conveyor rolls 84 which convey the sections to additional processing or storage points.

It is well known that ingots as conventionally produced by means of the above described continuous casting apparatus, have a peripheral fine-grained zone, an intermediate zone of relative coarse grain structure including columnar crystals and a central zone of somewhat fine grain structure, such as that above described with reference to Fig. 1. In continuous casting, however, the rapid chilling to which the molten metal is subjected, is conducive to the rapid formation of relatively large and coarse columnar grains. However, by the addition of the electromagnetic stirring apparatus hereinafter described, a randomly oriented, relatively fine grain structure can be obtained in ingots produced by continuous casting processes.

In accordance with the invention, the mold 67 is made of a non-magnetic material, e.g., copper, and is surrounded by a multiple pole, rotating magnetic field producing apparatus 85 which may be constructed in the same manner as the six-pole, rotating magnetic field producing structure described in connection with Figs. 5 and 6. When the device 85 has this form, it is maintained stationary and is energized from a three-phase power source.

Reverting to Fig. 5, it will be noted from an examination of the magnetic fields illustrated by the flux lines 49, that the greatest magnetic field concentration occurs in the outer peripheral portion of the molten metal 50. Accordingly, the greatest forces, and hence the greatest amount of stirring, occurs in the outer or peripheral zone of the molten metal. Thus, as applied to the continuous casting arrangement of Fig. 10, since the molten metal 66 flowing into the mold 67 remains molten in the peripheral zone thereof for only a relatively short time, it is important that the magnetic stirring forces or action be concentrated in the peripheral portion of the metal within the mold. It is for this reason that a stator having six or more poles is preferred for use in magnetically stirring the molten metal in this mold.

As the ingot 71 issues from the bottom of the mold 67, the central portion or core thereof is still molten. At this stage of the casting, the stirring action should be greatest near the central portion of the ingot 71 and although the central portion or core of the ingot 71 could be stirred by a device like the device 85, it is preferred that it be stirred by a two-pole, rotating magnetic field producing device 86 since the six-pole device creates too great a turbulence at the center of the ingot and tends to produce center porosity. The device 86 comprises a plurality of windings 87 mounted in slots in laminations 88 of magnetic material which are mounted in a housing 89.

Fig. 11 illustrates schematically the windings 87 of the device 86 and shows by means of the dotted lines 90 the distribution of the magnetic fields produced by such windings when connected in a well known manner to produce two magnetic poles, i.e., one north pole and one south pole. From an examination of Fig. 11, it will be seen that the magnetic field concentration obtained with the six-pole arrangement shown in Fig. 5. Accordingly, by connecting the windings 87 to a multiple-phase power source, in a well known manner, the device 86 will produce a rotating magnetic field in the ingot 71 which will effect greater stirring in the molten central portion of the ingot 71 than the six-pole device 85 described above. To

insure against center porosity, it has been found that the power supplied to the device 86 should be reduced over that supplied to device 85.

In many cases, sufficient stirring of the metal forming the ingot 71 will be obtained by the use of only the devices 85 and 86. However, if desired, further stirring of any remaining molten central portion of the ingot 71 may be produced by means of an additional stirring device 92 mounted as shown in Fig. 10; but, in any event the power should be reduced as the center of the ingot solidifies. The stirring device 92, for the reasons set forth above, is preferably a two-pole electromagnetic stirring device having the same construction as that at 86.

Reverting to the magnetic flux concentration of the two-pole stator of Fig. 11, versus that for the six-pole stator of Fig. 5, it may be stated quite generally that at any given frequency of A.C. supply, that two-pole stator produces greater magnetic flux concentration at the center of the molten metal than in the peripheral regions of the bath. Conversely, a stator providing a greater number of magnetic poles, preferably six or more, gives greater flux concentration in the peripheral regions of the molten metal bath than at the center. For a stator of any given number of magnetic poles, the relative degree of magnetic flux penetration toward the center of the molten metal bath is approximately inversely proportional to the square root of the frequency of A.C. power supply. Thus, the flux penetration becomes greater as the frequency of power supply is decreased.

Having thus described the invention with particular reference to the preferred form thereof and having described certain modifications, it will be obvious to those skilled in the art to which the invention pertains, after understanding the invention, that various changes and other modifications may be made therein without departing from the spirit and scope of the invention, as defined by the claims appended thereto.

We claim as our invention:

1. The method of minimizing columnar grain growth during cooling and solidification of a molten bath of an iron base alloy contained in a mold which comprises: progressively cooling and solidifying said metal from the exterior surface adjacent said mold to the interior thereof while subjecting said bath to a magnetic field in the direction of the thermal gradient of said cooling and while relatively displacing said field continuously with respect to said molten metal in a direction substantially perpendicular to the direction of said thermal gradient, said magnetic field being such that the constant

$$WH^2a^2=K$$

is in the range of

$$10^9 \text{ to } 10^{10} \frac{\text{oersteds}^2 \text{ cms.}^2}{\text{sec.}}$$

where W is the rate of rotation of the magnetization vector of said field within an element of metal near the liquid-solid interface of the cooling metal, H is the magnetic field intensity in oersteds, and a is determined by casting a production size test ingot of said alloy in the absence of a magnetic field, sectioning and etching the ingot and measuring the length from the ingot center to the point at which columnar grain growth begins during solidification of the ingot.

2. The method claimed in claim 1 in which the ratio is in the range of

$$2.0 \times 10^9 \text{ to } 4.8 \times 10^9 \frac{\text{oersteds}^2 \text{ cms.}^2}{\text{second}}$$

3. The method of minimizing columnar grain growth during cooling and solidification of a molten bath of an iron base alloy contained in a mold of elongated configuration relative to its transverse sectional area, which comprises: progressively cooling and solidifying said

molten metal from the exterior longitudinal surface thereof adjacent said mold, toward its longitudinal axis while subjecting said bath to a magnetic field in the direction substantially perpendicular to said longitudinal axis and while relatively displacing said field rotatively with respect to said molten metal about said magnetic axis, said magnetic field being such that the constant

$$WH^2a^2=K$$

is in the range of

$$10^9 \text{ to } 10^{10} \frac{\text{oersteds}^2 \text{ cms.}^2}{\text{sec.}}$$

where W is the rate of rotation of the magnetization vector of said field within an element of metal near the liquid-solid interface of the cooling metal, H is the magnetic field intensity in oersteds, and a is determined by casting a production size test ingot of said alloy in the absence of a magnetic field, sectioning and etching the ingot and measuring the length from the ingot center to the point at which columnar grain growth begins during solidification of the ingot.

4. The method of minimizing columnar grain growth during cooling and solidification of a molten bath of an iron base alloy contained in a mold of substantially cylindrical configuration, which comprises: progressively cooling and solidifying said metal from its exterior cylindrical surface adjacent said mold towards its longitudinal axis while subjecting said bath to a magnetic field in a direction substantially perpendicular to said axis and while relatively displacing said field rotatively with respect to said molten metal about said axis, said magnetic field being such that the constant

$$WH^2a^2=K$$

is in the range of

$$10^9 \text{ to } 10^{10} \frac{\text{oersteds}^2 \text{ cms.}^2}{\text{sec.}}$$

where W is the rate of rotation of the magnetization vector of said field within an element of metal near the liquid-solid interface of the cooling metal, H is the magnetic field intensity in oersteds, and a is determined by casting a production size test ingot of said alloy in the absence of a magnetic field, sectioning and etching the ingot and measuring the length from the ingot center to the point at which columnar grain growth begins during solidification of the ingot.

5. The method of minimizing columnar grain growth during cooling and solidification of a molten bath of iron base alloy in a substantially cylindrical mold of non-magnetic material, which comprises: casting said molten metal into said mold and progressively cooling and solidifying said molten metal therein from the exterior cylindrical surface thereof adjacent said mold towards the longitudinal axis of said mold while subjecting the metal to a magnetic field in a direction substantially perpendicular to said axis and while relatively displacing said field with respect to said mold at a substantially uniform

angular velocity about said axis, said magnetic field being such that the constant

$$WH^2a^2=K$$

is in the range of

$$2.0 \times 10^9 \text{ to } 4.8 \times 10^9 \frac{\text{oersteds}^2 \text{ cms.}^2}{\text{sec.}}$$

where W is the rate of rotation of the magnetization vector of said field within an element of metal near the liquid-solid interface of the cooling metal, H is the magnetic field intensity in oersteds, and a is determined by casting a production size test ingot of said alloy in the absence of a magnetic field, sectioning and etching the ingot and measuring the length from the axis of said ingot to the point at which columnar grain growth begins during solidification of the ingot.

6. A method of minimizing columnar grain growth during cooling and solidification of a molten bath of a metal selected from the group consisting of iron base alloys, magnetic non-ferrous metals and alloys thereof, comprising casting said molten metal into a mold of non-magnetic material, progressively cooling and solidifying said molten metal from the exterior surface thereof adjacent said mold towards the longitudinal axis of said mold, simultaneously subjecting said molten metal to a magnetic field in a direction substantially perpendicular to said axis, and simultaneously relatively rotating said field and said mold and said metal contained therein about said axis, said magnetic field being such that, for iron base alloys, the constant

$$K=WH^2a^2$$

is in the range of

$$2.0 \times 10^9 \text{ to } 4.8 \times 10^9 \frac{\text{oersteds}^2 \text{ cms.}^2}{\text{sec.}}$$

and, for magnetic non-ferrous metals, the constant

$$K'=K(R)$$

where W is the rate of rotation of the magnetization vector of said field within an element of metal near the liquid-solid interface of the cooling metal, H is the magnetic field intensity in oersteds, a, in centimeters, is determined by casting a production size test ingot of the bath metal in the absence of a magnetic field, sectioning and etching the ingot and measuring the length from the axis of the ingot to the point at which columnar grain growth begins during solidification of the ingot, and R is the ratio of electrical resistivity of molten, magnetic, non-ferrous bath metal to that of molten iron.

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