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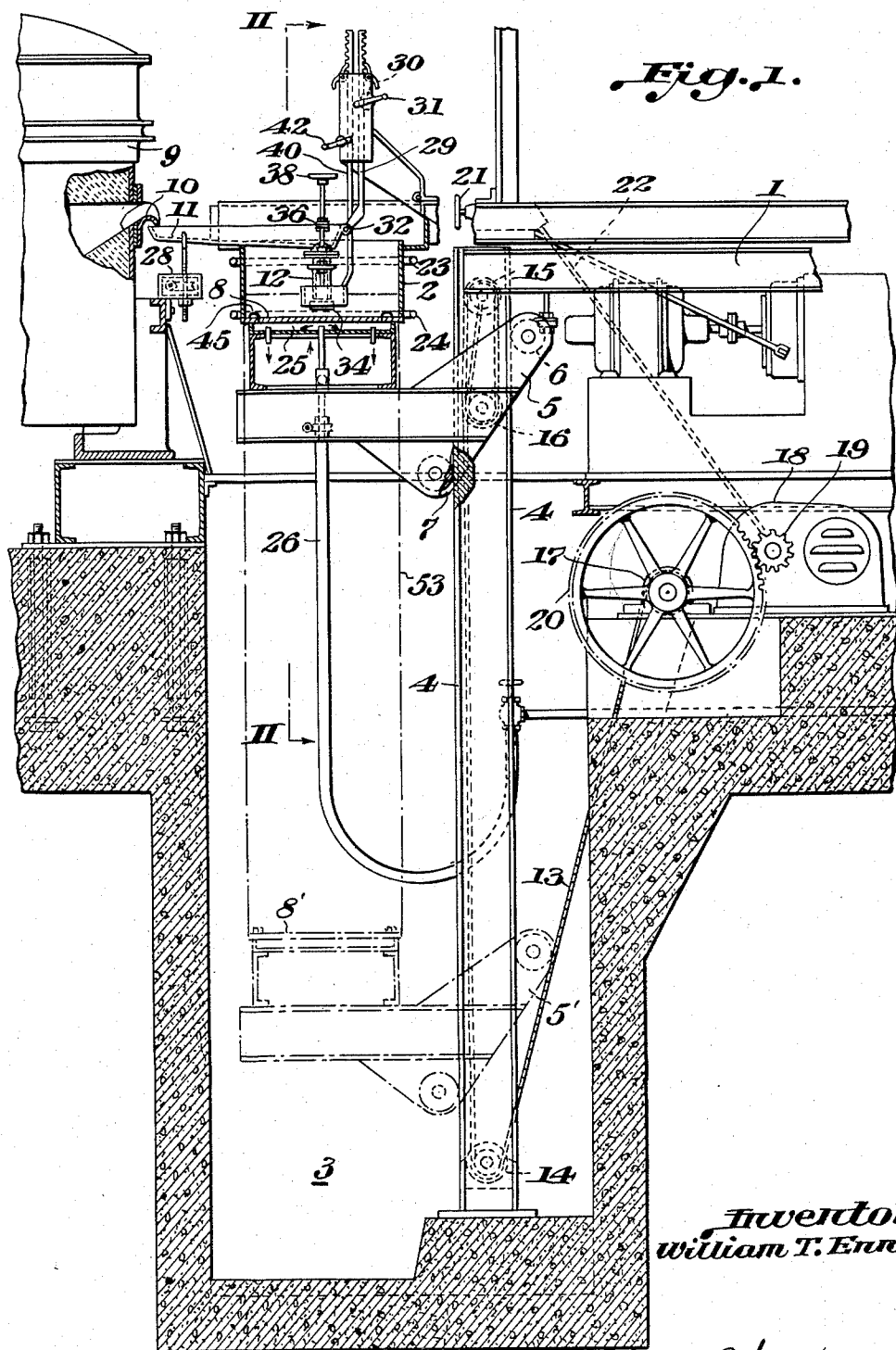
W. T. ENNOR

2,301,027

METHOD OF CASTING

Filed July 2, 1938

5 Sheets-Sheet 1



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Nov. 3, 1942.

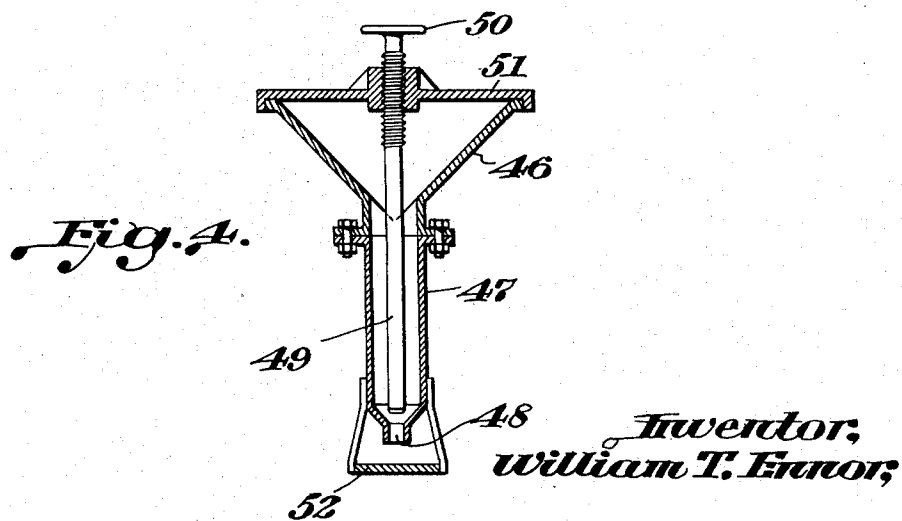
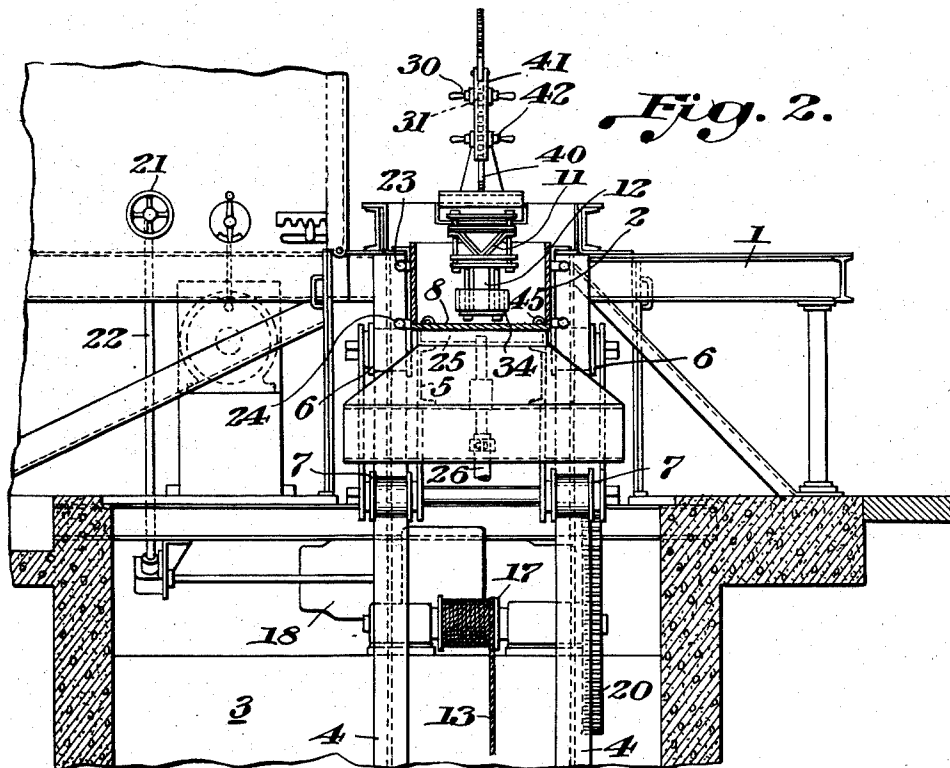
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METHOD OF CASTING

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5 Sheets-Sheet 2



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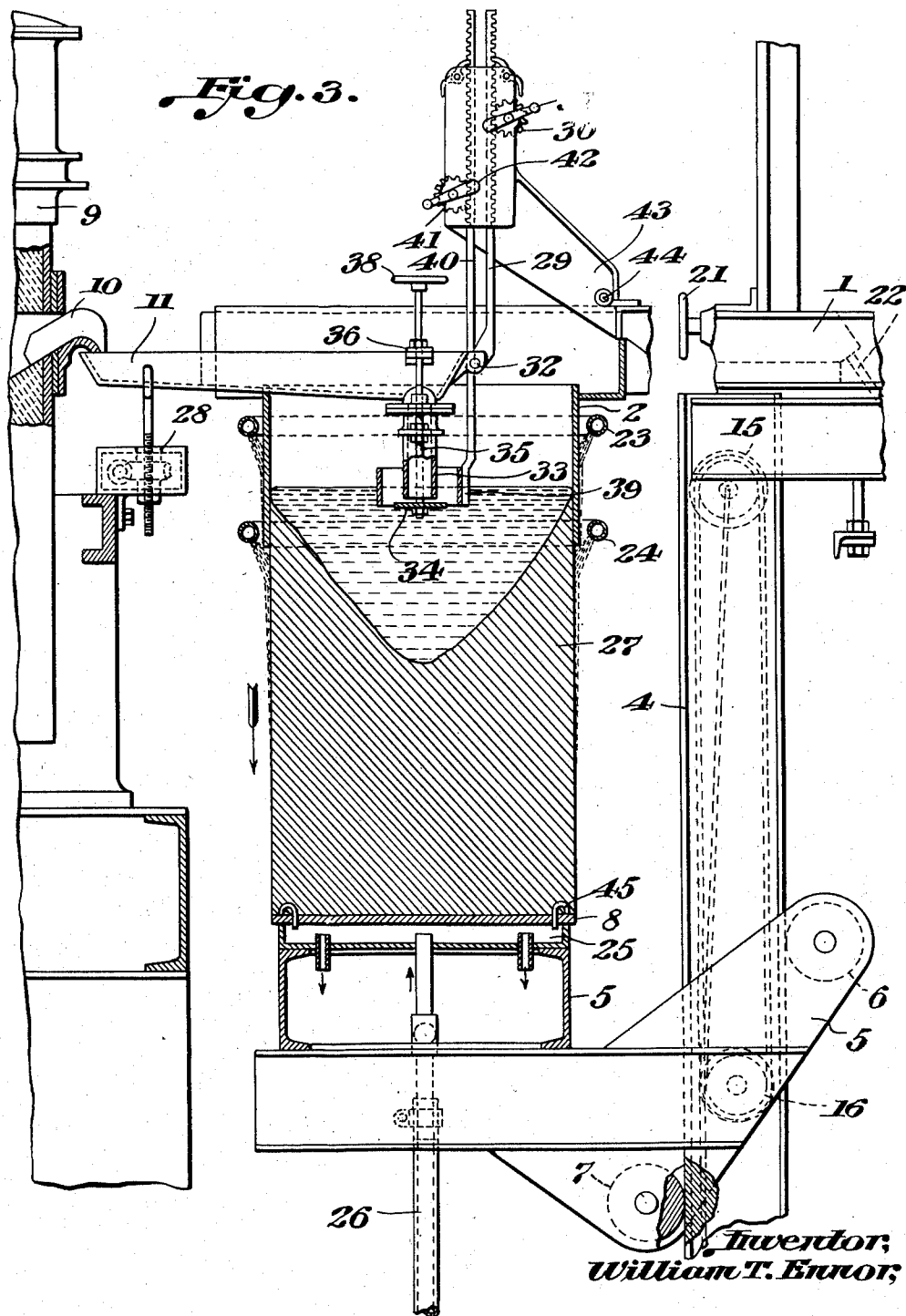
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5 Sheets-Sheet 4

Fig. 5

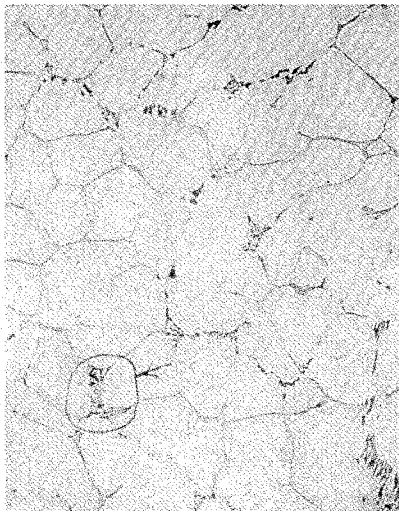


Fig. 6

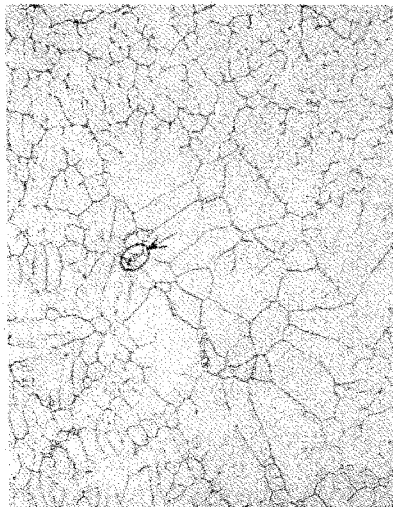


Fig. 7

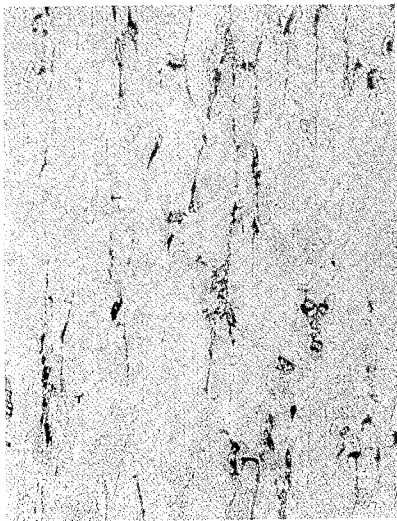
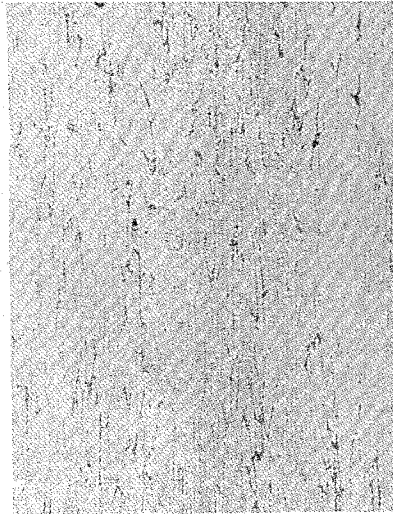


Fig. 8



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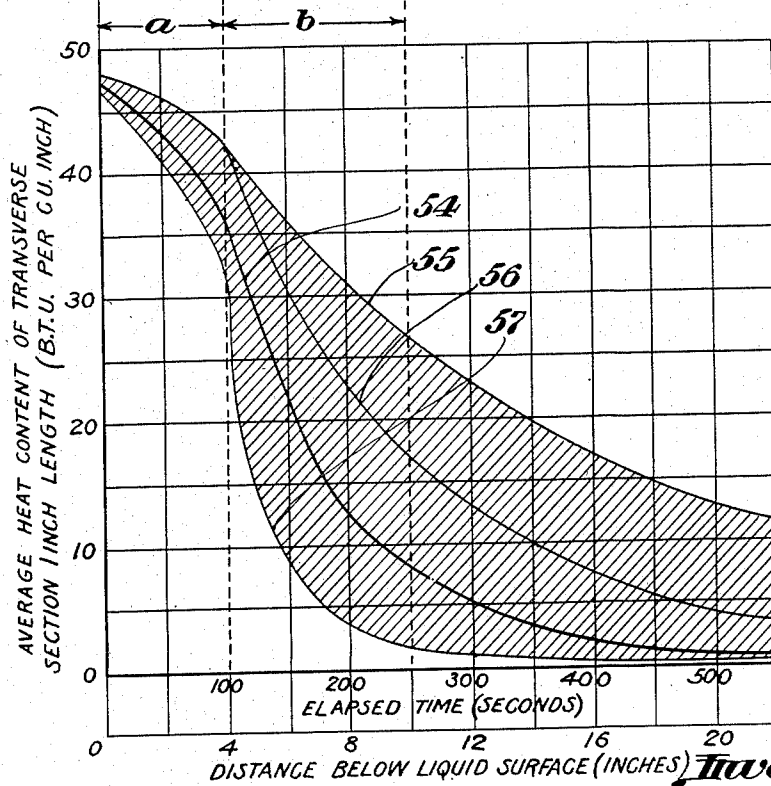
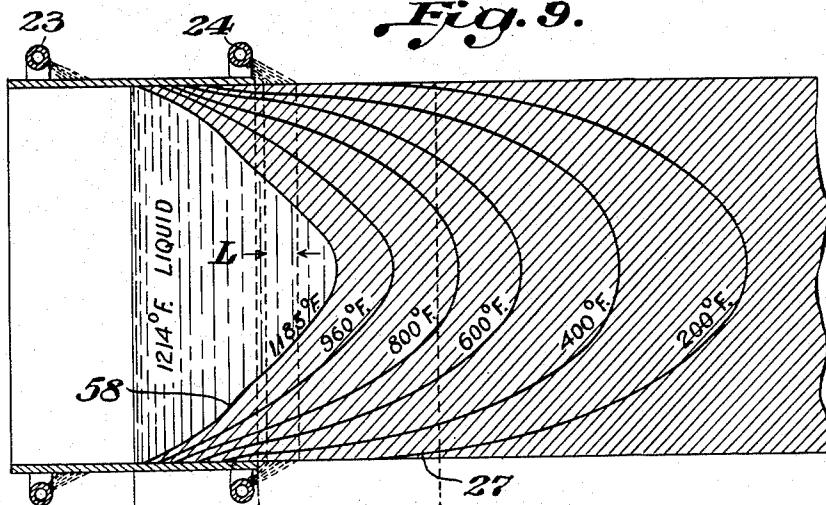
2,301,027

METHOD OF CASTING

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5 Sheets-Sheet 5

Fig. 9.



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UNITED STATES PATENT OFFICE

2,301,027

METHOD OF CASTING

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Application July 2, 1938, Serial No. 217,200

14 Claims. (Cl. 22—200.1)

This invention relates to the casting of ingots of light metals and alloys thereof, by which latter terms I mean aluminum and its alloys and magnesium and its alloys. The invention is particularly adapted to the production of ingots of large cross section and indeterminate length.

Particularly, in the production of large structural shapes and forgings of aluminum and its alloys, larger and larger ingot has been required. Larger ingots of magnesium and its alloys are also desirable. Ingot casting methods which had proved satisfactory in the production of ingots of the smaller cross sections were tried out in the production of the new sizes called for today, but the results were not at all satisfactory. The larger ingot was unsound or the structure of the metal so inferior as to lead to difficulties in subsequent working. Among the difficulties encountered, the cracking of the ingot during working and the unsatisfactory final heat-treated properties of the metal were found to be particularly serious. These and other considerations appear to depend upon the structural characteristics of the metal as cast.

I have observed that the working characteristics of light metal ingot are determined largely by the size and distribution of the undissolved alloying constituent. If the undissolved constituent is coarse, i. e. present in the form of relatively large isolated particles, and therefore less uniformly distributed than is to be desired, the working characteristics are far less satisfactory than where there is a finer and more uniform distribution.

The detrimental effects of a coarse constituent distribution show up in two different ways in light metal fabrication. First, coarse and uneven distribution of the constituent frequently results in cracking of the ingot at some stage during the working of the metal. One manifestation of this is the cracking of the surfaces, edges or corners of the ingot during the initial break-down stages. Again, cracking may occur at the center of the ingot. A particular difficulty which has been encountered is the cracking that occurs during the later stages of fabrication under severe conditions of stress. Examples of this which may be mentioned are: the cracking encountered in rolling large structural shapes which in the case of some channel sections shows up along the flanges; the cracking of the edges of plates and slabs; and that which occurs around the periphery of metal being upset under a forging hammer.

The second manner in which a coarse constitu-

ent network can be injurious is its effect in producing unsatisfactory properties in the final heat-treated product of these working operations. In extremely large products, this may be true regardless of the direction in which a test sample is taken. For example, the mechanical properties of large round or square sections after heat-treatment may be unsatisfactory even in the direction of rolling—i. e. longitudinally. As the amount of working is increased, the constituent network tends to be broken up and the properties improved. This improvement is quite noticeable in the longitudinal direction, but in the transverse direction the harmful effect of the coarse constituent network persists even after a very extensive working of the metal.

A better understanding of the nature of the problem presented, and therefore of the objects of this invention which concern its solution, can be gained from a consideration of the methods heretofore devised to the same end. At first it was thought that the solution lay in increasing the amount of work, and therefore the extent of the breaking-up of the constituent network, by starting with ingot of larger size. This has failed to provide the solution. When casting the ingot by known methods, it was found that the increase in ingot size results in an increase in coarseness of the constituent network, and that this largely nullifies the beneficial effect of the increased amount of hot working. Also, in breaking down the larger ingot with its coarser constituent network, fracturing of the central regions of the ingot becomes a more frequent and serious occurrence.

It has been known heretofore that in casting light metal ingot of very large cross section the manner of cooling the ingot influences the tendency to form dendritic grain structures, and the freedom from the defects of segregation, liquation and porosity. The best practice prior to the time of the present invention is described in the Stay and Holzhauer Patents Nos. 1,777,657 and 1,777,658, granted October 7, 1930. According to the method of these patents, the metal in the mold is progressively and gradually solidified from the bottom to the top of the mold. This method is quite satisfactory in producing ingot for many purposes but does not produce ingot having a sufficiently fine and even distribution of the undissolved alloying constituent to avoid altogether the various types of fabrication difficulties which have been described, or to make possible the attainment of satisfactory mechanical properties in heat-treated articles of the

large sizes now demanded by the light metal market.

With reference to the casting of ingot in general, attempts have been made to feed the metal into a mold continuously while withdrawing the partially cooled metal down through the bottom of the mold and applying a liquid coolant to the surface of the metal below the mold. These methods were not adapted to the casting of light metal ingot of large cross section, principally because the cooling was not performed in a manner to produce in such ingot a metal structure having a sufficiently fine and even distribution of the undissolved alloying constituent.

It is an object of the present invention to provide a method of casting aluminum ingot of large cross section which will possess improved working characteristics and make possible the attainment of improved mechanical properties in large wrought and heat-treated articles made therefrom.

More particularly, it is an object of my invention to provide a method of casting light metal ingot which will not be subject to the various types of cracking described hereinabove as occurring during break-down or later working stages.

A general object is to provide an ingot casting method by which sound light metal ingot may be produced, which ingot is particularly characterized by the fineness and evenness of distribution of its alloying constituent, with especial reference to the network of the undissolved constituent. A pictorial representation of this object is given in Figs. 6 and 8 of the drawings, later to be described; it being an object of my invention to provide an ingot casting method by which there can be produced an aluminum ingot (of the alloy represented) which, as to fineness and evenness of distribution of the undissolved constituent, will approximate the microstructure of this representation.

A further object is to provide a method by which production of large light metal alloy ingot of the stated characteristics may be carried on economically and by which ingot of any desired length may be produced.

A further object is to provide apparatus for carrying out the novel method, including a novel form of mold and metal feeding means by which the novel steps of the method are performed.

A specific object is to provide a method of abstracting heat from metal cast to form an ingot whereby initially the heat may be withdrawn principally by absorption of radiant energy without metal-to-mold contact.

Other objects and advantages will appear as the description proceeds.

The drawings illustrate an embodiment of the apparatus for carrying out the method, the microstructure of the aluminum alloy ingot produced, and a graphical representation of essential steps of the general method.

Apparatus.—Fig. 1 is a side elevation, partly in section, showing a general arrangement of apparatus suitable for carrying out the method. Fig. 2 is an elevational view on the line II—II of Fig. 1 showing a portion of the same apparatus. Fig. 3 is a vertical sectional view, to an enlarged scale, of the mold, ingot platform and metal-feeding arrangement of Figs. 1 and 2; the parts being shown in the position occupied at an intermediate point in the casting operation. Fig. 4 is a vertical sectional view of a modified metal-feeding device.

Photomicrographs.—Fig. 5 is a photomicrograph, magnification 100 diameters, of the metal structure at the center of a 12" x 12" aluminum alloy ingot as cast by the method described in the aforementioned Stay and Holzhauser Patent No. 1,777,657, granted October 7, 1930. Fig. 6 is a photomicrograph, magnification 100 diameters, of the metal structure at the center of a 12" x 12" ingot of the same aluminum alloy as that represented in Fig. 5 as cast by the method of the present invention. Fig. 7 is a photomicrograph, magnification 100 diameters, showing, in longitudinal section, the metal structure at the center of a 6" x 6" bloom as rolled from the ingot of Fig. 5. Fig. 8 is a photomicrograph, magnification 100 diameters, showing, in longitudinal section, the metal structure at the center of a 6" x 6" bloom as rolled from the ingot of Fig. 6.

Graphs.—Fig. 9 is a graphical representation of essential steps of the general method.

Reference will first be had to Figs. 1 to 4, inclusive, illustrating an embodiment of the apparatus for carrying out the method. Figs. 1 and 2 show a general arrangement of such apparatus, in which a main frame structure 1 supports a mold shell 2 conveniently located above a casting pit 3. A portion of the main frame structure 1 consists of a column extending down into the casting pit 3, which column, in the structure shown, takes the form of I-beams 4, 4. The I-beams 4, 4 serve as a vertical runway or track for the carriage 5 which is provided with two pairs of flanged wheels 6, 6 and 7, 7 bearing against the flanges of I-beams 4, 4 on opposite sides thereof. The carriage 5 carries a horizontal platform 8 and supporting structure therefor, which platform forms the bottom of the mold.

Metal is fed into the mold from an electric pouring ladle 9 through the pouring spout 10, adjustable trough 11, and cooperating vertical feeding means 12.

The carriage 5 with the mold bottom 8 is arranged for vertical movement which, in the apparatus illustrated, is accomplished by means of cable and winch. A cable 13 passes over fixed pulleys 14 and 15 mounted in the column formed by the I-beams 4, 4 and over a movable pulley 16 mounted in the carriage 5, and is secured adjacent the fixed pulley 15. Cable 13 is wound over a drum 17 supported in the main frame 1. This winding drum 17 is driven by a variable-speed motor 18 acting through the pinion 19 and gear wheel 20, which latter is keyed to the same shaft as the winding drum 17.

The lowering rate of the carriage 5 may be controlled by any well known means, as by the variable-speed motor 18 here shown, the speed of which can be controlled from the operating platform by means of the hand wheel 21 acting through the control shaft 22.

Means are provided for cooling the mold shell 2 and also for directly chilling the embryo ingot as it is lowered below the plane of the bottom edge of the mold shell. This cooling is preferably accomplished by means of a water spray directed around the periphery of the mold shell by means of spray pipes 23 and 24, the water jets or spray from which act respectively against the outer surface of the mold shell 2 and the surface of the embryo ingot as it emerges therebelow. I prefer also that the mold bottom 8 be cooled as by means of water delivered into the cooling chamber 25 through a pipe and flexible hose connection 26.

The metal feeding means is shown to a larger scale in Fig. 3, in which the mold bottom 8 has been lowered so that the embryo ingot 27 is seen emerging from the bottom of the mold shell 2. The pouring trough 11 is vertically adjustable at the ladle end by any suitable means 28 (see also Fig. 1) so as to bring it into the proper position to receive the molten metal from the pouring spout 10 of the ladle. The other end of the pouring trough 11 likewise is provided with a vertical adjustment as by the rack 29 and pinion 30 with its operating crank 31, the pouring trough 11 being pivotally supported on the lower end of the rack 29 as at 32. Extending below the pouring trough 11 is a vertical standpipe 33 in communication with the trough at its upper end, and at its lower end being open to the mold. Opposite the lower end of standpipe 33 is a horizontal baffle plate 34 supported on rods 35 which pass through projections 36 on either side of trough 11. These rods 35 are threaded in the projections 36 to provide a vertical adjustment for the baffle plate 34 by turning the handles 38 on the rods 35. This adjustment is used to vary the opening between the bottom of standpipe 33 and the baffle plate, thereby to control the rate of discharge of the molten metal from the lower end of the metal feeding means. I have found it desirable to employ a skimmer 39, consisting of a vertical baffle plate arranged to form an enclosure around the feeding device at the level of the metal in the mold. This skimmer 39 may be provided with a vertical adjustment similar to that used for the pouring trough 11 and consisting of a rack 40 and pinion 41 operated by a crank 42.

It will be noted that the various adjustments described in connection with the pouring trough 11 and skimmer 39 provide for introduction of the metal without turbulence at various levels within the mold shell 2, thus permitting the maintenance of any desired head of metal in the mold, the term "head" being used here to indicate the depth of the metal in the mold shell 2, i. e., the distance from the plane of the lower edge of the mold shell to the surface of the molten metal. This arrangement likewise makes it possible to lift the pouring trough and standpipe assembly, 11, 33 out of the mold, and when the skimmer 39 is raised to an extent permitted by the rack and pinion 40, 41, the rack support 43 which is hinged to the main frame 1 at 44 can be tilted back out of the way at the end of the ingot casting operation.

A modified form of metal feeding device is shown in Fig. 4 in vertical cross section, looking toward the ladle. Here the pouring trough is represented at 46, and the standpipe or pouring tube at 47. In this form, the standpipe is restricted at its lower end to form the orifice 48. The flow of the metal through the orifice 48 is controlled by the rod 49 which acts as a valve, being raised or lowered by turning the handle 50 to operate its screw-threaded engagement with the rod support 51. Below the orifice 48 is a horizontal baffle plate 52 which in this case is not adjustable with respect to the standpipe or pouring tube. This modified form of metal feeding arrangement may be used in conjunction with the skimmer, mold and other parts illustrated in Fig. 3.

In the preferred practice of my invention, the inner walls of the mold shell 2 are provided with a layer of solid lubricant, preferably grease. Under some conditions of operation, it may be

found that a wax or other non-metallic substance serving to space the molten metal from the walls of the mold shell may be used with good results. I have found in particular that a solid lubricant produces marked advantages over a liquid. It need not be renewed at any time during the casting of even the largest and longest ingot, due to my surprising discovery that, even under the action of the molten metal which is continuously cast into the mold against the layer of lubricant and drawn past it, a very appreciable amount of the lubricant remains in place on the mold walls—in fact, an amount readily visible to the naked eye and which can be rubbed off with the finger.

In operation, the mold bottom 8 is brought up into the position which it occupies in Figs. 1 and 2, and the metal feeding means 11, 33 and skimmer 39 lowered into the mold 2, as shown in these figures. Wire clips 45 may be inserted in the mold bottom (see Fig. 3), these clips being bent underneath the mold bottom 8 and also being hooked over at their upper ends in such a way that the first metal cast in the mold, when solidified around the clips 45, is fastened to the mold bottom 8. This insures that, at the beginning of the casting operation when the mold bottom first begins to move downwardly, the embryo ingot will likewise start to move downwardly. Once the operation is well under way, the weight of the cast metal insures its continuous travel down through the mold. Now with the parts in the position described, the electric pouring ladle 9 is tilted by means of any of the mechanisms well known for this purpose (not shown) so that the molten metal flows into the trough 11 and down through the standpipe 33 against the horizontal baffle plate 34 and laterally outwardly toward the mold shell 2 underneath the lower edge of the skimmer 39. As the metal reaches the bottom and edges of the mold, it is cooled by the water in the chamber 25 and the water spray 23, beginning to solidify around the periphery. As soon as the metal in the mold has built up to the desired head, as determined in accordance with the size and shape of the cross section of the ingot, the rate of lowering of the metal through the mold, and character of the particular alloy being cast, the motor 18 is started in order to lower the carriage 5 and mold bottom 8 at the predetermined rate. For aluminum alloys of the type now in use commercially in the production of the large structural shapes and forgings from the ingot produced by my method, I have found it is advantageous to employ lowering speeds of between 1 and 7 inches per minute. After the lowering speed and thickness of metal head within the mold have been selected, the horizontal baffle plate 34 and level of the molten metal in the trough 11 are adjusted to maintain these conditions in equilibrium during the entire casting operation. As the embryo ingot passes out of the mold and below the plane of the lower edge thereof, it is chilled directly by the water spray from the pipe 24. This spray impinges against the surface of the embryo ingot on all sides and runs down the sides thereof. Ingot of any desired length may be produced in this manner, and the operation is terminated at the desired moment by interrupting the flow of metal into the mold, whereupon the completed ingot is withdrawn entirely below the mold and removed from the casting pit. A completed ingot is indicated by the dot dash lines 53 in Fig. 1.

In this specification, the term "embryo ingot" is used to refer to the ingot in the process of

formation, and includes all of the metal below the upper liquid surface down to the point where the lowest freezing eutectic of the metal is entirely solidified. "Effective area" of the mold walls is used with reference to that portion of the inner surface of the mold shell 2 which lies between the plane of the upper liquid surface of the metal in the mold (for a given head) and the plane of the lower edge of the mold shell.

Attention is directed to the fact that the head of metal in the mold is relatively small in comparison with the size of the ingot's cross section. This is of importance in producing a light metal and particularly an aluminum or aluminum alloy ingot possessing the desirable characteristics outlined in the statement of object. Another factor of importance is the rapid rate of lowering of the embryo ingot through the mold shell. These factors, together with the rate of application of the liquid coolant directly to the surface of the embryo ingot as it emerges below the mold shell, govern the temperature gradient within the embryo ingot, and therefore the rate at which heat is abstracted in cooling the metal to below its solidus or below the temperature at which the lowest freezing eutectic has entirely solidified. These factors also determine what portion of the total heat content of the ingot above room temperature is withdrawn through the mold walls, or which is withdrawn from that portion of the embryo ingot which lies above the plane of the bottom edge of the mold shell.

It is, of course, obvious that the factors under discussion must be varied in accordance with the shape of the cross section of the ingot, whether it is a solid or a hollow ingot, or whether it is round, square or rectangular. In general, a common denominator is provided by the minimum transverse dimension of the ingot cross section; for it is this dimension which largely determines the proper distance between the molten metal and the point of direct application of the liquid coolant to the surface of the embryo ingot.

It will be recalled that one of the stated objects of the invention is to provide an ingot casting method by which sound aluminum ingot may be produced, which ingot is particularly characterized by the fineness and evenness of distribution of its alloying constituent, with especial reference to the network of the undissolved constituent. This object may best be explained with reference to Figs. 5 to 8, inclusive, of the drawings which will now be described in greater particularity. Fig. 5 is a photomicrograph, magnification 100 diameters, of the metal structure at the center of a 12" x 12" aluminum alloy ingot as cast by the method described in the aforementioned Stay and Holzhauser Patent No. 1,777,657, granted October 7, 1930. The alloy is one of the common strong aluminum alloys much in use today, containing about 4.0 per cent of Cu, about 0.5 per cent Mn, and about 0.5 per cent Mg. The cell area, constituent particle size, and particularly the dendritic segregation of insoluble constituent should be noted for purposes of comparison with Fig. 6 which is a photomicrograph, magnification 100 diameters, of the metal structure at the center of a 12" x 12" ingot of the same aluminum alloy as that represented in Fig. 5 as cast by the method of the present invention. The points to be noted in comparing Fig. 6 with Fig. 5 are: smaller cell areas, greater uniformity of distribution of constituents, smaller particle size of constituents (also evident from the increase in the number of particles present),

and the strikingly lesser extent of dendritic segregation of insoluble constituents. Two such corresponding areas are indicated by circles in Figs. 5 and 6.

Fig. 7 shows the metal structure at the center of a 6" x 6" bloom as rolled from the ingot represented in Fig. 5; and Fig. 8 shows the metal structure at the center of a 6" x 6" bloom as rolled from the ingot represented in Fig. 6. Both of these photomicrographs are at the magnification of 100 diameters and are longitudinal sections. Refinement of the constituent particle size and the uniformity of distribution thereof in the bloom rolled from ingot produced in accordance with my method, for instance as in Fig. 8, is characteristic, and will be seen to be far superior to that produced in a bloom rolled from the same alloy as cast by the best method known to the art prior to the present invention (Fig. 7). Of particular importance is a marked decrease in the extent of dendritic segregation of insoluble constituent in the structure of Fig. 8. The areas of dendritic segregation are represented by the dark particles in Fig. 7, but these areas are difficult to distinguish in Fig. 8 by reason of their small size.

I have found that, by holding within certain limits the percentage of the total heat content of the metal which is abstracted at the mold, the rate of such abstraction of heat, and the rate of abstraction of heat from the embryo ingot immediately below the plane of the bottom edge of the mold down to the point where the lowest freezing eutectic is entirely solidified, it is possible to produce, as cast in ingot of very large cross section, a metal such as represented in Fig. 6, and which is characterized by a structure in which the undissolved constituent is uniformly distributed in finely divided form; which possesses, to an extent heretofore unattained in ingot of large cross section, the desirable working characteristics visibly represented in Fig. 8 (75 per cent reduction by rolling); and which is remarkably free from cracking during severe working operations leading to the production of finished wrought and heat-treated articles of superior mechanical properties, examples of which will be given hereinbelow.

The limits within which the rate of heat abstraction from that portion of the embryo ingot which lies above the plane of the bottom of the mold shell and that which lies immediately below such plane must be maintained, in order to obtain the advantages of the present invention, may best be explained with reference to the diagrammatic representation of Fig. 9. In the graph of Fig. 9, I have plotted, as abscissae, elapsed time in seconds and, as ordinates, the average heat content (above room temperature) of a transverse section through the embryo ingot one inch in length as expressed in B. t. u. per cubic inch. A scale ancillary to the abscissa scale of elapsed time is provided to show the distance of the section considered below the liquid surface in inches for any given elapsed time.

Curves plotted to these coordinates show the falling off in heat content of the metal as it passes down through the mold and past the point at which the lowest freezing eutectic solidifies. The diagram at the top of Fig. 9 is plotted against the same elapsed time and distance scales as form the abscissa for the graph. Consider a section whose length L is one inch (length being used herein to refer to dimensions parallel to the longitudinal axis of the ingot), as it passes

down through the mold from the upper liquid surface to the plane of the lower edge of the mold shell 2 and on past this plane to a point beyond which the lowest freezing eutectic has solidified. According to my invention, this last point will never lie appreciably beyond a distance equal to one-half the minimum transverse dimension of the ingot section. That portion of the embryo ingot which lies above the plane of the bottom edge of the mold shell 2 is represented by the dimension a , and that portion which lies immediately below the plane of the bottom edge of the mold and which is of a length equal to one-half the minimum transverse dimension of the ingot section is represented by the dimension b . The rate of cooling of the embryo ingot over the time and distance $a+b$ is of critical significance in achieving the objects and results of my invention. Within limits depending primarily upon the shape of the ingot cross section, and upon other considerations such as the composition of the alloy, the dimension a (regarded either as time or distance) is variable; and dimension b , by definition, varies according to the minimum transverse dimension of the ingot section. However, within the limits of variation of a and b , the rate at which heat is withdrawn in order to produce my improved ingot structure is illustrated in the graph.

The curve 54 over an elapsed time of 250 seconds, which may be represented as 54_{a,b}, depicts the rate of loss in average heat content of a transverse section one inch in length for an ingot, exemplified by the microstructure of Fig. 6, as cast by my improved method. In the diagram at the top of Fig. 9, this typical ingot is represented in the process of formation, isotherms being plotted along the central vertical cross section thereof for temperatures of 1185 degrees F., 960 degrees F., 800 degrees F., 600 degrees F., 400 degrees F., and 200 degrees F. Above 1185 degrees F., the alloy may be considered to be in the liquid state. For the ingot represented, the average temperature of the metal as introduced at the liquid surface of the metal in the mold was 1214 degrees F. The ingot represented was 12"x12" in cross section and was cast of an aluminum alloy containing about 4.0 per cent Cu, 0.5 per cent Mn and 0.5 per cent Mg. After I had discovered the critical cooling rates within which the improved metal structure could be obtained, careful calorimetric measurements were made in order that a better understanding of the theory of the invention might be obtained. A water trough was constructed around the outside of the lower edge of the mold shell 2 in order that the quantity and final temperature of the water used to cool the mold shell might be determined, and an accurate figure be obtained for the amount of heat abstracted through the mold shell 2. Thermocouples were arranged in the mold in such a way as to travel downwardly therethrough with the embryo ingot during the casting process, providing the data from which were plotted the isotherms shown in the diagram.

The curve 54_{a,b}, takes into account the latent heat of fusion of the metal, and, by its slope, indicates the change in rate of heat abstraction as a unit of length of the metal passes downwardly through the mold over the distance $a+b$. It is to be noted that a definite though relatively small portion of the heat is removed over the time and distance a , and that the average rate of heat abstraction over the distance b is greater than that over the distance a , as shown by the increase

in average slope of curve 54_b over curve 54_a. I have found that, in order to produce the improved metal structure typified by that of an ingot cooled at the rate represented by the curve 54_{a,b}, it is necessary to cool the mold shell while simultaneously applying a liquid coolant directly and rapidly to the metal below the mold shell at a rate adjusted to withdraw from that portion of the embryo ingot which lies above the plane of the bottom edge of the mold shell at least 2 B. t. u. per minute per cubic inch average per inch of length averaged over the length of said portion and to withdraw from that portion of the embryo ingot which lies immediately below the plane of the bottom edge of the mold shell at least 6 B. t. u. per minute per cubic inch average per inch of length averaged over the length b which is equal to one-half the minimum transverse dimension of the ingot section. Curve 55_{a,b}, provides a graphical representation of these limits. In some cases, for example, with alloys of the type described hereinabove, I have found it preferable to withdraw from that portion of the embryo ingot which lies immediately below the plane of the bottom edge of the mold shell at least 10 B. t. u. per minute per cubic inch average per inch of length averaged over the length b . Curve 56_{a,b}, provides a graphical representation of this preferred limit when combined with the limit of 2 B. t. u. per minute per cubic inch average per inch of length for the rate of withdrawal of heat from that portion of the embryo ingot which lies above the plane of the bottom edge of the mold shell. Curves 55 and 56 coincide over the time and distance a . Curve 57_{a,b} is not critical with respect to the attainment of the objects of the present invention and may vary according to the size and shape of the ingot cross section. It will be understood that there is a limit beyond which the slope of the curve 57_b cannot practicably be increased, and the curve 57_b has been shown merely to indicate what I consider as, in general, a practicable minimum cooling rate over the distance b .

The shaded area between the curves 55_{a,b} and 57_{a,b}, represents the cooling rates at the mold and below the mold within which the advantages of my invention may be attained for the ingot shown, and I consider that the limiting conditions represented by curve 55_{a,b} are critical.

I have found further that, in order to produce the best results, not more than between 7 and 25 per cent of the total heat content of the metal above room temperature should be withdrawn through the mold shell, and that if the cooling rate is adjusted to within these limits and a liquid coolant is applied directly and rapidly to the metal below the mold shell to withdraw the balance of the total heat content, a metal structure such as that illustrated in Fig. 6 can readily be obtained.

One of the novel features of my method resides in carrying a shallow metal head within the mold shell, that is, looking at Fig. 9, the dimension a is quite shallow with respect to the cross sectional dimensions of the ingot. This makes it possible to apply the liquid coolant from the spray pipe 24 directly to the surface of the embryo ingot at points not farther removed from the level of the surface of the molten metal in the mold than twice the minimum transverse dimension of the ingot, thus to produce a sharp temperature gradient in cooling the metal to below the solidus. The cooling rate over the distance a is determined, in part, by the heat withdrawn through

the mold shell 2, and, in part by the heat withdrawn by the direct application of the liquid coolant from the spray pipe 24 below the lower edge of the mold shell 2. It is to be noted that the rate of cooling through the shell and the rate of cooling below the shell may bear such a relation to each other as to produce irregularities in the shape of the isotherms. In some cases this effect may be observed as indicated at 53 in Fig. 9 and the observations which I have made appear to indicate such a manifestation.

When other conditions heretofore defined have been satisfied by adjusting the rate at which molten metal is introduced into the mold shell 2 and the rate at which the metal is lowered through the mold as well as the points at which the liquid coolant is applied directly to the metal through the spray pipe 24, its temperature and quantity, a sharp temperature gradient will be maintained from the center of the ingot to the sides thereof. More specifically, it will be found that from all points on the ingot surface in a horizontal plane just below the bottom of the mold shell, the mean minimum distance to the molten metal will be maintained at not greater than one-half of the smallest transverse dimension of the ingot. The metal at the ingot center will still be molten in the horizontal plane at which the liquid coolant is applied directly to the ingot surface but should not be molten at a greater distance below the plane of the bottom of the mold shell than the minimum transverse dimension of the ingot. Conversely, when these conditions are satisfied by making the named adjustments, the conditions otherwise defined will have been satisfied, and the principal objects of my invention realized.

It is quite essential to the successful practice of my invention that the molten aluminum be introduced into the mold shell in a manner to produce quiet, radially outward flow of the metal toward the mold shell near the top surface of the metal in the mold. The apparatus for accomplishing this has been described with reference to Figs. 3 and 4 of the drawings, in which the horizontal baffle means 34 or 52 are utilized. The metal as it reaches the surface of the metal in the mold is directed outwardly in all directions toward the mold shell 2 where it is cooled principally by the abstraction of radiant energy without metal-to-metal contact between the introduced metal and the mold walls, whereby a controlled and relatively small amount of the total heat content of the metal is withdrawn through the mold. The horizontal baffle means restricts the downward flow of the metal entering the mold. In the preferred practice of my method, the temperature of the mold walls at the level of the metal surface in the mold is maintained below 200 degrees Fahrenheit.

Reference has already been made to the maintenance of a relatively shallow head *a* of metal in the mold shell 2. This feature of the method is perhaps best defined with reference to the apparatus employed. In order that a relatively small and controlled amount of heat be abstracted from the metal at the mold, that is, above the plane of the lower edge of the shell 2, it is necessary that the effective area of the mold walls be restricted according to the cross sectional area of the ingot. I have found that the effective area of the mold walls should not be more than three times the cross sectional area of the ingot—preferably from one to three times its cross sectional area. For most ingot sizes, the lowering speeds will vary between 1 and 6 inches per minute.

I shall now describe a specific example of the practice of my invention. A 12" x 12" bronze mold shell such as illustrated in the drawings was prepared by coating its interior walls with a film of heavy grease. The mold bottom was raised into the position shown in Figs. 1 and 2, the metal feeding means, skimmer, and horizontal baffle means lowered into position in the mold shell, and the cooling water turned on in the spray pipes 23, 24, and in the flexible hose connection 26 feeding the cooling chamber 25. The electric pouring ladle 9 was then tilted to feed metal into the pouring trough 11 and downwardly through the vertical feeding means 12. As soon as the head of metal had built up to 4 inches above the plane of the lower edge of the mold shell 2, the motor 18 was started and the hand wheel 21 adjusted to lower the carriage 5 and the mold bottom 8 at a speed maintained at about 2.4 inches per minute. The metal was an aluminum alloy comprising 4.0 per cent Cu, 0.5 per cent Mn, and 0.5 per cent Mg, balance substantially aluminum plus impurities, and was maintained at a temperature averaging 1214 degrees Fahrenheit at the surface of the molten metal in the center of the mold. The rate of application of the cooling water was adjusted to withdraw from that portion of the embryo ingot which lay above the plane of the bottom edge of the mold shell 6.5 B. t. u. per minute per cubic inch average and to withdraw from that portion of the embryo ingot represented at *b* in Fig. 9, 11 B. t. u. per minute per cubic inch average. When the ingot had reached a length of 8 feet, the metal feeding was discontinued, the ingot cooled and removed. The ingot was then heat-treated at 930 degrees Fahrenheit for 6 hours and quenched in water. Test samples taken from ingot so produced were subjected to tensile tests with the following average results:

Location of test sample	Elongation	Tensile strength
	Per cent in four diameters	Pounds per sq. in.
Transverse center	8.5	43,600
Transverse, one-half way to surface	7.0	46,800

These properties are superior to those obtained by the best practice known prior to my invention, which, for ingot of the same size and alloy composition, shows elongations on the order of 2.8 to 3.5 per cent in four diameters and tensile strengths on the order of 35,800 to 39,100. Although the values obtained by the best prior methods may sometimes be greater than this, no consistency is to be expected at figures greater than those given. The ingot as produced by the method just outlined was free from objectionable cracking, its metal structure characterized by the fineness and evenness of distribution of its alloying constituent, and large wrought and heat treated articles made therefrom possessed improved mechanical properties. Most of the stock rolled from large ingot produced in accordance with my method gives very high values in transverse tests, such values as 55,000 pounds per square inch tensile strength with 15 to 18 per cent elongation being common.

While I have described my invention particularly with reference to aluminum, it is applicable also to magnesium and its alloys and thus broadly relates to the common light metals

and light metal alloys. The principles specifically described hereinabove with reference to one of these light metals—aluminum—may also be used with success in the casting of the other light metal—magnesium. For example, it has been found that a magnesium base alloy composed of magnesium and about 1.5 per cent manganese can be successfully cast in the form of a 7" x 16" ingot from which very satisfactory sheet can be rolled. This was accomplished by heating the alloy to a pouring temperature of about 1400° F., transferring it to the mold shell in the manner described hereinabove. A 3 inch head of metal was maintained in the mold and the ingot lowered at a rate of about 4 inches per minute. The mold shell was lubricated in the same manner as was done in casting aluminum alloy ingots, and the water sprays were likewise adjusted to deliver about the same volume of water as was used in making aluminum alloy ingots of the same size. The ingot was rolled to sheet form without difficulty, the sheets being of a quality equal to, or better than, sheets obtained from ingots cast according to older methods.

My method and apparatus are useful in the casting of hollow ingot as well as for casting the solid form specifically shown and described. In the case of hollow ingot the liquid coolant may be applied to the interior as well as the exterior surfaces of both the mold shell and the ingot. I intend to cover all such modifications of the invention described as fall within the purview of the claims.

This application is a continuation-in-part of my application for United States patent filed October 14, 1936, Serial No. 105,631.

I claim:

1. In the casting of ingots of light metals and alloys thereof by continuously pouring metal into a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in the shell an embryo ingot, adjusting and maintaining the withdrawal of heat through the shell and below the same to provide a sharp temperature gradient between the sides of the ingot and the freezing metal as exemplified by the fact that the molten metal does not extend below the plane of emergence to a distance greater than the minimum transverse dimension of the ingot, and adjusting and maintaining the pouring rate and the rate of withdrawal of the ingot from the shell to maintain the upper surface of the molten metal close to the plane of emergence of the embryo ingot from the shell.

2. In the casting of ingots of light metals and alloys thereof by continuously pouring metal into a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in the shell an embryo ingot, adjusting and maintaining the withdrawal of heat through the shell and below the same to provide a sharp temperature gradient between the sides of the ingot and the freezing metal, and adjusting and maintaining the pouring rate and the rate of withdrawal of the ingot from the shell so that the effective area of the mold wall will not be more than three times the cross-sectional area of the ingot.

3. In the casting of ingots of light metals and

alloys thereof by continuously pouring metal into a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in the shell an embryo ingot, adjusting and maintaining the pouring rate and the rate of withdrawal of the ingot from the shell and the withdrawal of heat through the shell and below the same, so that from all points on the outside surface of the ingot which lie in the plane of emergence of the ingot from the shell the mean distance to molten metal will be not greater than one-half the smallest transverse dimension of the ingot, and so that metal at the ingot center will still be molten in the plane of emergence of the ingot but will not be molten at a greater distance below said plane than the minimum transverse dimension of the ingot.

4. In the casting of ingots of light metals and alloys thereof by continuously pouring metal into a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in and through the shell an embryo ingot, adjusting and maintaining the pouring rate and the rate of withdrawal of the ingot from the shell, and the withdrawal of heat through the shell and below the same, so that from all points on the outside surface of the ingot which lie in the plane of emergence of the ingot from the shell the mean distance to molten metal will be not greater than one-half the smallest transverse dimension of the ingot, and so that the total depth of molten metal above the lowest point of unsolidified metal is less than the minimum transverse dimension of the ingot.

5. In the casting of ingots of light metals and alloys thereof by continuously pouring metal into a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in the shell an embryo ingot, adjusting and maintaining the pouring rate and the rate of withdrawal of the ingot from the shell and the withdrawal of heat through the shell and below the same, so that metal at the ingot center will still be molten in the plane of emergence of the ingot but will not be molten at a greater distance below said plane than the minimum transverse dimension of the ingot.

6. In the casting of ingots of light metals and alloys thereof by continuously pouring metal into a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in the shell an embryo ingot, adjusting and maintaining the withdrawal of heat through the shell and below the same to provide a sharp temperature gradient between the sides of the ingot and the freezing metal, and adjusting and maintaining the pouring rate and the rate of withdrawal of the ingot from the shell to maintain the upper surface of the molten metal close to the plane of emergence of the embryo ingot from the shell, and so that from all points on the outside surface of the ingot which lie in the plane of emergence of the ingot from the shell the mean distance to molten metal will be not greater than one-half the

smallest transverse dimension of the ingot, and so that metal at the ingot center will not be molten at a greater distance below said plane of emergence than the minimum transverse dimension of the ingot.

7. In the casting of ingots of light metals and alloys thereof by continuously pouring metal into a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in the shell an embryo ingot, adjusting and maintaining the withdrawal of heat through the shell and below the same to provide a sharp temperature gradient between the sides of the ingot and the freezing metal, and adjusting and maintaining the pouring rate and the rate of withdrawal of the ingot from the shell to maintain the upper surface of the molten metal close to the plane of emergence of the embryo ingot from the shell, so that metal at the ingot center will not be molten at a greater distance below the plane of emergence of the ingot from the shell than the minimum transverse dimension of the ingot.

8. In the casting of ingots of light metals and alloys thereof by continuously pouring metal into a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in the shell an embryo ingot, and adjusting and maintaining the withdrawal of heat through the shell and below the same so that between about 7 and 25 per cent of the total heat content of the metal above room temperature is continuously withdrawn through the shell, thereby to produce a sharp temperature gradient between the sides of the ingot and the freezing metal.

9. In the casting of ingots of light metals and alloys thereof by continuously pouring metal into a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in the shell an embryo ingot, and adjusting and maintaining the withdrawal of heat through the shell and below the same so that between about 7 and 25 per cent of the total heat content of the metal above room temperature is continuously withdrawn through the shell, thereby to produce a sharp temperature gradient between the sides of the ingot and the freezing metal, and adjusting and maintaining the pouring rate and the rate of withdrawal of the embryo ingot from the shell to maintain the upper surface of the molten metal close to the plane of emergence of the ingot from the shell.

10. In the casting of ingots of light metals and alloys thereof by continuously pouring metal into

a downwardly open mold shell and withdrawing part of the heat from the metal through the shell and part of the heat through the metal below the shell, the improvement comprising forming and moving downwardly in the shell an embryo ingot, while adjusting and maintaining the pouring rate and the rate of withdrawal of the embryo ingot from the shell to maintain a metal head within the shell which is shallow with respect to the cross-sectional dimensions of said ingot, and to provide that the molten metal does not extend below the plane of emergence to a distance greater than the minimum transverse dimension of the ingot.

11. The process of solidifying molten metal into ingot which comprises continuously supplying molten metal to a vertically disposed mold and continuously withdrawing metal from said mold while maintaining only a small amount of molten metal in said mold as evidenced by the fact that the total depth of molten metal above the lowest point of unsolidified metal is less than the minimum transverse dimension of the ingot.

12. The process of casting light metals and alloys thereof which comprises continuously supplying molten metal to a vertically disposed mold, continuously withdrawing metal from said mold, and maintaining the upper surface of molten metal in said mold close to the plane of emergence of the ingot from said mold as evidenced by the fact that the lowest point of unsolidified metal lies below the plane of emergence at a distance no greater from the said upper surface of molten metal than the minimum transverse dimension of the ingot.

13. In the method of continuous casting of metal in a thin molding tube of high thermal conductivity cooled by a flowing thin sheet of fluid in contact with the outer walls of the tube, the step of maintaining on the inner wall of the tube a film of lubricating material having a melting point substantially lower than that of the metal being cast.

14. In the process of solidifying molten metal into ingot which comprises continuously supplying molten metal to a mold shell, the ends of which are open, and withdrawing at least a part of the heat from the metal through said shell, the improvement comprising adjusting and maintaining the withdrawal of heat and the rate of withdrawal of the metal from the shell so that the distance, as measured along the center line of the body of metal in the direction of its travel, between a plane perpendicular to the said direction of travel and containing the point at which solidification of metal first begins and a plane perpendicular to the said direction of travel and containing the point at which all solidification is first completed shall not be greater than the minimum transverse dimension of the ingot.

WILLIAM T. ENNOR.

CERTIFICATE OF CORRECTION.

Patent 2,301,027.

November 3, 1942.

WILLIAM T. ENNOR.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows: Page 3, second column, line 16, for "ocupies" read --occupies--; page 5, second column, line 43, for "minimum" read --maximum--; page 8, second column, line 56, claim 14, for "solidificatoin" read --solidification--; and that the said Letters Patent should be read with this correction therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 8th day of December, A. D. 1942.

Henry Van Arsdale,
Acting Commissioner of Patents.

(Seal)