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TWO-STAGE METHOD FOR THE CASTING OF FUSIBLE MATERIALS

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This invention relates to a method for the casting of fusible materials which have a higher density in the solid state than in the liquid state in a continuous or discontinuous manner and, more particularly, for the casting of metals in a continuous manner.

In the casting of a fusible material, heat must be removed from the outer surface of the molten material, with the result that the outer parts of the casting are the first to solidify. An outer skin of solid material is first formed around the outer surface of the molten material and progressively thickens as heat is removed from the material until the entire mass is solid. In the case of the great majority of materials, the mass shrinks as it solidifies and draws away from the mold. In the casting of metals, solidification from the outer surface causes the concentration and segregation of foreign matter in the innermost parts of the casting which frequently is accompanied by a dendritic crystal growth which results in a non-uniform, and usually a coarse grain structure.

The problems created by or associated with the removal of heat increase with the size of the casting being produced and with the thermal capacity of the material being cast. The problems involved are also dependent upon the shape of the casting being produced. Thus, in the case of a casting which has sharp angles on its outer surface, heat is removed from the material being cast in the vicinity of the sharp angles at a faster rate than from the flat or gently curved areas of the surface, with the result that strains are set up in the vicinity of the sharp angle of the solidified casting which frequently results in cracks in those areas.

The problems involved in the removal of heat are more serious in the continuous casting of fusible materials than in discontinuance or batch-wise casting. The difficult problems involved in the case of non-ferrous materials, such as copper and aluminum, which have relatively low fusion temperatures and high thermal conductivities have been solved to an extent such that they are being successfully cast in a continuous manner on a commercial scale. The problems involved are even more difficult in the continuous casting of steel and steel alloy products and have not been satisfactorily solved.

The basic apparatus for the continuous casting of metals includes a liquid cooled mold which is open at both ends, and is designed to receive molten metal at its upper end and for the withdrawal of the casting from the lower end. In the continuous casting of copper, aluminum and their alloys, special cooling methods and apparatus are necessary to avoid over-heating and failure of the mold, especially in the zone of maximum heat transfer adjacent the molten metal level, despite their relatively low solidification temperatures.

In a commercial form of apparatus for the casting of copper and aluminum, a relatively low uniform rate of supply of molten metal to the mold is employed to reduce the total quantity of heat to be transferred during any time interval and the position of the mold rela-

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tive to a constant molten metal level is continuously altered at a relatively low frequency and low amplitude, to place any portion of the mold in zone of maximum heat transfer for only a brief time interval and remove it therefrom before mold damage results. Such continuous, reciprocating molds are now in commercial operation in the casting of copper, brass, aluminum and aluminum alloys.

In the continuous casting of aluminum and copper, a high percentage of the heat which must be removed from the molten metal flows downwardly through the ingot, since the solid metal has a high heat conductivity. For this reason, the sump of molten metal in the top of the casting is shallow and a condition in which a hot, weak, metal skin must contain molten metal under pressure is not developed. On the other hand, in the continuous casting of a ferrous metal, such as ordinary steel, the heat flow is almost exclusively radial, because the already solidified lower portion of the casting is ineffective in the removal of heat from the molten metal due to its relatively low thermal conductivity. The result is the formation of a deep, paraboloidal sump of molten metal in the top of the casting, in which molten metal under a hydraulic pressure head is retained by a thin skin of hot metal which is relatively weak.

In any metal casting, as the molten metal is cooled by contact with the inner surface of the mold wall, the thin skin of solidified metal which is first formed has little strength and will remain in contact with the mold wall by reason of the static head of the molten metal. As this skin increases in thickness to form a shell, it becomes the first heat barrier between the molten metal and the mold wall. The consequent temperature gradient through this solidified shell results in cooling it to a temperature at which it has sufficient strength to overcome the static head of metal, and to contract, pulling away from the mold wall. The resulting gap between the shell of the casting and the mold wall forms a second heat transfer barrier.

This second heat transfer barrier is likely to be formed during the continuous withdrawal of the casting from a mold even before contraction of the casting produces a gap, since a casting mold is seldom absolutely uniform in internal cross-sectioned area and configuration at succeeding sections along its length. In fact, it is practically impossible to insure the maintenance of continuous contact between the mold wall and the surface of the moving casting.

The formation of these heat transfer barriers and the resultant drop in the heat transfer rate to the mold cooling medium causes a re-heating of the solidified metal and a thinning and expansion of the previously solidified shell. A continuance of this re-heating of the shell frequently results in a rupture of the shell under the static head of metal and causes a run-out of molten metal. Molten metal issuing from a rupture in the shell of a casting which is still in the mold fills the gap between the casting and the mold wall and tends to solidify and jam the casting in the mold. Such a shell rupture in a portion of the casting below the mold permits the molten metal core of the casting to drain leaving an empty shell.

The transition from the liquid to the solid state of many fusible materials, including steel and alloy steels, takes place over a range of temperatures, the limits of which depend upon the chemical composition of the materials. Molten, mild steel, for example, begins to solidify or crystallize upon cooling at its liquidus temperature and remains in a two-phase state until its solidus temperature is reached. Between the liquidus and solidus temperatures one of the phases is a solid solution delta and the other is liquid iron. The alloy has little or no cohesive

strength within this range, which is sometimes termed the "mushy" range. Although steel freezes less mushy than the non-ferrous metals, because of its low conductivity, the mushy range causes serious problems in the continuous casting of steel due to the formation of the deep paraboloidal sump of molten metal in the top of the casting.

The extent of this mushy range, the higher liquidus temperatures and the lower thermal conductivity of steel, in comparison with the lower freezing points and the higher thermal conductivities of copper and aluminum, are largely responsible for the great difficulty which has been encountered in the continuous casting of steel and steel alloys. Thus, the liquidus temperature of most steels is of the order of 750° F. higher than the freezing point of copper and 1500° F. higher than that of aluminum. The thermal conductivity of most steels is only 3% to 12% that of copper and 6% to 23% that of aluminum. The higher temperature of crystallization and the higher heat content of molten steel require a much greater rate of heat abstraction from the heat receiving surface of a mold wall to maintain that surface at a temperature which will keep the mold wall at a safe metal temperature during the formation of an embryo casting than in the continuous casting of copper or aluminum.

The low thermal conductivity of steel and the mushy transition stage through which many types of steel pass result in the formation of an elongated, inverted, cone shaped molten core surrounded by a similarly elongated mushy core which introduces serious metallurgical problems in the continuous casting of ferrous alloys. One of the problems is the porosity of steel castings. The porosity is caused both by gas inclusions and by the change in the specific volume of the metal which takes place in the solidification of the molten metal combined with a lack of feed of molten metal to the embryo casting to fill the voids formed during the solidification of the metal.

In the melting of copper and aluminum, the comparatively low temperatures have little or no disintegrating effect on the lining of the furnace and other receptacles in which the metal is handled, with the result that little foreign material is carried into the metal. As a result, there is practically no slag removal problem in the continuous casting of copper and aluminum.

In the continuous casting of steel and removal of slag presents a major problem. In the production of steel, the development of slag is a prerequisite to the purification of the metal. The high temperatures in the furnaces and receptacles in which molten steel is handled, combined with the fact that iron compounds and many of the non-metallic impurities in the slag attack refractories commonly used in the furnaces and receptacles magnify the problems involved.

Any slag and impurities carried down into a continuous mold tend to accumulate on the surface of the molten metal until it is cooled to a viscous condition. A slight rise in the liquid metal level in the mold causes the slag to be entrapped in the periphery of the casting. The presence of an accumulation of slag in or near the surface of a casting is objectionable in itself. In addition, such an accumulation creates other problems. Any heavy slag accumulation entrapped in or on the thin shell of an embryo casting will tend to insulate the adjacent portion of the casting from the removal of heat by the inner surface of the mold. The shell strength of such an insulated portion of the casting is frequently insufficient to withstand the internal ferrostatic pressure imposed thereon and results in a rupture of the shell, with consequent jamming in the mold or even a draining of the molten core of the casting to leave it a hollow shell. Further, it has been observed that a delay in the solidification of the interior portions of a casting adjacent an outer portion insulated by slag, and its subse-

quent solidification and contraction sometimes results in the development of internal shrinkage with the formation of cracks and voids in the area.

The measure of economic efficiency of any continuous casting unit is the volume or the weight of the cast material produced per unit of time. The heat content of molten steel per cubic foot is 70-75% more than that of molten copper per cubic foot and 350% more than that of molten aluminum per cubic foot. Hence, to maintain the same volumetric rate of production in the continuous casting of steel, copper and aluminum, respectively, using casting molds of identical cross-section, the heat absorption characteristics of the mold wall used with steel must be 70-75% better than the mold wall used with copper and about 350% better than the mold wall used with aluminum.

It is an important object of this invention to reduce the quantity of heat which must be removed from a fusible material in a single-stage in the production of a casting of the material and thereby eliminate or reduce the difficulties arising from the removal of large quantities of heat through the wall of a casting mold.

Another object of this invention is to provide centers within a molten material being cast from which crystallization or solidification can proceed and minimizes undesirable segregation of impurities in the interior of the casting and, in the case of metals, undesirable dendritic crystal growth and coarse grain structures.

Another object is to provide a method which minimizes or entirely eliminates many of the difficulties heretofore encountered in the continuous casting of ferrous and non-ferrous metals and materially increases the rate at which such casting can be carried out, and thereby greatly increases the economic efficiency of such casting operations.

A further object is to provide a method which reduces or eliminates difficulties which have heretofore made the continuous casting of ferrous metals on a commercial scale impractical and unattractive from an economic standpoint. More specifically, it is an objective of this method to materially reduce the depth of the deep paraboloidal sump formed in the continuous casting of ferrous metals and thereby largely or completely eliminate the serious difficulties caused thereby. An associated objective is to eliminate or minimize the segregation of slag in the continuous casting of ferrous metals which has heretofore caused serious defects in such castings.

A still further object is to provide a method which is adapted for use in conjunction with existing procedures for the continuous casting of ferrous and non-ferrous metals and the apparatus developed therefor without extensive changes and modifications, while materially improving the overall thermal efficiencies of the casting operation and relieving the casting mold of a substantial part of its burden in removing heat from the fused metal.

Other objects of this invention and its various advantageous features will become apparent as this description proceeds.

In principle, this invention involves the casting of a fusible material which has a higher density in the solid phase than in the liquid phase by the removal of the heat of fusion and any super-heat which may be present in the fused material in two distinctive steps. By operating under specifically controlled conditions, which will be fully described hereinafter, I am able to produce a casting in the second step of this method in a materially shorter time and avoid many difficulties which heretofore have been encountered in both the discontinuous and the continuous casting of fused materials.

The method in accordance with this invention for the casting of a fused material which has a lower density in the liquid phase than in the solid phase comprises the steps of removing the heat of fusion from a portion of the fused material to be used in the production of a cast-

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ing to form a plurality of individual particles or pieces of the fused material in the solid phase, and of admixing these solid particles with the remainder of the fused material in a casting mold and removing any residual super-heat and the heat of fusion of the liquid phase of this solid-liquid mixture to produce a homogeneous solid. The proportion of the fused material which is solidified in the first of these steps is such that it can be admixed with the remainder of the still fused material to produce a solid-liquid mixture which will accurately conform to the internal surface of the casting mold used in the second step. Furthermore, the relative proportions of these two phases and their temperatures at the time of their admixture are adjusted to provide a total amount of heat in the mixture which will cause at least an incipient fusion of the solid particles in the mixture.

The great majority of fusible materials have a higher density in the solid phase and can be cast by the method of this invention. A material which has a reversed density relationship causes difficulty in this method, particularly in the continuous embodiment of this method, since the solid phase will concentrate itself at the surface of the liquid phase. Fortunately, materials which expand on freezing are relatively rare. Bismuth, antimony, gallium and water are the only such materials of even minor importance in the present connection.

In carrying out this method, the particles or pieces of solid material produced in the first step must fall within a definite range of sizes, although the exact particular size within the range is largely immaterial. On one hand, they should be large enough to overcome the surface tension of the fused material when placed on its surface and settle through the liquid phase with a reasonable rate of fall. Thus, for example, in an embodiment of this method in which the second step is carried out in a continuous manner and the solid particles are added continuously to a sump of molten metal on the top of the casting in an amount totalling, for example, 30% by volume of the total metal being cast, I prefer to have about 50% by volume of solid particles collected in the bottom of the sump with not more than 10% by volume near the top of the molten metal at any given instant. Solid particles which are small enough to be retained near the surface of the liquid phase cause difficulty in mixing the two phases and even when the difficulties are avoided, for example, by injecting the solid particles below the surface of the liquid phase they show no particular advantages over larger particles and are generally more difficult and more expensive to produce in the first step of my method. Furthermore, small particles have a large surface per unit volume which is oxidizable or oxidized and potentially dirty. This large surface is undesirable and tends to create a serious problem when the solid phase is pre-heated, in accordance with my preferred procedure described hereinafter. I have found that it is usually desirable to produce a solid phase in the first step of this method which has an average particle size greater than about 500 microns and is usually preferable to use considerably larger particles.

On the other hand, the solid particles should be sufficiently small as compared with the smallest dimension of the casting, which is to be produced, to avoid any tendency to bridging during their addition to the liquid phase. In general, I prefer to have the average cross-sectional dimensions of the largest particles of the solid not more than one-tenth the smallest dimension of the casting. It is usually convenient and desirable to produce a solid phase having an average particle size small as compared with the smallest dimension of the usual castings produced by this method.

The pieces or particles of the fusible material which I produce in the first step of this method are preferably of a reasonably compact shape, i. e. any shape in which the dimension in one or more directions is not a large multiple of its dimension in other directions. I have

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found that a spherical or substantially spherical shape is convenient to produce in the first step as, for example, by the use of a shot tower in which the fused material is solidified while in free fall through a fluid cooling medium. Although, in some cases I may utilize a liquid cooling medium in the production of these particles, a gaseous cooling medium such as, for example, air or a non-oxidizing gas, such as nitrogen, is usually more convenient for the purpose.

The proportion of the fused material which is solidified to form a plurality of solid particles or pieces in this first step and the extent to which the temperature of these solid particles or pieces are cooled below their solidification temperature are controlled in relation to the extent to which the fused material is super-heated at the time it is mixed with the solid particles in the casting mold in the second step of this method to produce a heat balance in the liquid-solid mixture in the casting mold which results in a partial or complete refusion of the solid particles in the mold. This control relationship may be reversed. Thus, the extent to which the fused material is super-heated at the time it is mixed with the solid particles from the first step may be controlled, in terms of the proportion of the solid particles in the mixture and the extent to which they are cooled below their solidification temperature, to produce a heat balance in the liquid-solid mixture in the casting mold which results in a partial or complete refusion of the solid particles in the mold. However, this reversed control is of limited value, since the liquid phase must usually carry a limited quantity of super-heat to assure complete conformation of the surface of the liquid-solid mixture with the internal surface of the mold, but should be kept at a minimum to minimize the quantity of heat which must be removed from the liquid-solid mixture to produce a solid casting. For this reason, I normally utilize the first mentioned control relationship in carrying out this method.

A partial or complete refusion of the solid particles in the second step of this method is usually necessary to secure a homogeneous casting. In the alternative in which I use an initial heat balance in the second step which results in a complete refusion of the solid phase of the mixture, this method eliminates the necessity for removing a part or all of the super-heat from the liquid phase of the mixture. The solid particles, of course, carry no super-heat and the super-heat of the liquid phase is largely utilized as heat of fusion in the melting of the solid particles. Therefore, in this alternative, only a little more than the heat of fusion of the entire mass in the mold need be removed from the fused material through the inner wall of the mold and the time required for cooling is shortened.

In carrying out this method, it is usually advantageous to use an initial heat balance in its second step which produces no more than an incipient fusion of the surfaces of the solid particles of the mixture. I have found that such incipient fusion is entirely adequate to produce a homogeneous, continuous casting. When utilizing such an initial heat balance in the second step, it is necessary to remove only the heat of fusion of the liquid phase and that of the very minor part of the solid phase which is remelted. In this alternative, there is no super-heat to be removed, since the initial super-heat of the liquid phase has been absorbed in raising the temperature of the solid phase to its fusion temperature and in furnishing heat of fusion for the minor part of the solid phase which is remelted in the incipient fusion of its surfaces.

In the alternative in which there is no more than an incipient refusion of the surfaces of the solid particles in the second step of my method, there is even less opportunity for the segregation of impurities and, in the case of metals, little opportunity for dendritic crystal growth. The result is an even greater improvement in the quality of the casting.

From the foregoing, it will be understood that in the

casting of a given material by the method of this invention, the variables which must be considered in fixing the conditions required of an initial solid-liquid mixture in the second step of the method to produce a heat balance which causes at least an incipient surface fusion of the solid particles are the fusion temperature of the material, the temperature at which the solid particles enter the mixture, the temperature at which the fused liquid enters the mixture, i. e. the extent to which it is superheated, and the relative volumetric proportions of the solid and liquid phases of the mixture, and that the size of the solid particles, within the range of particle sizes mentioned hereinbefore, has little effect on the heat balance involved. I have found that the relationship between these controlling variables may be defined by the equations given below. These equations are simplified by neglecting the difference between the liquid and solid specific heats of the material being cast. However, the difference between the liquid and the specific heats of a fusible material is almost always small enough to make no change in the value of the variables which are significant from the standpoint of their control in commercial operations.

As will be fully illustrated by specific examples, these equations may be used in determining the value at which a given variable must be fixed to fulfill the minimal requirement of my method for the incipient fusion of the surface of the surfaces of solid particles when the other variables are fixed.

Equation I

$$(1-f)T_1 + fT_s \geq T_m$$

In this equation, f is the fraction of the liquid-solid mixture which is in the solid phase, T_1 is the Fahrenheit temperature of the fused material entering the mixture, T_s is the Fahrenheit temperature of the solid particles entering the mixture and T_m is the Fahrenheit fusing temperature of the material.

Equation I defines the broadest range of conditions under which I can obtain a minimal heat balance in the second step of my process and is controlling, for example, when the solid particles are at or near normal atmospheric temperatures when admixed with the liquid phase. As shown by the equation, the super-heat carried by the liquid phase of the mixture must be in excess of the heat required to bring the solid phase of the mixture to its melting point. The excess heat is required to furnish the heat of fusion required for the incipient fusion of the surface of the solid particles in the mixture, and need be only a small quantity.

In operating under the minimal conditions required by Equation I, using solid particles at low temperature, for example at or near atmospheric temperature, the incipient fusion of the surfaces of the solid particles may be slow and the liquid phase may solidify on the surfaces of the liquid particles in the form of a thin skin which is refused before incipient fusion of the surfaces of the solid particles takes place.

In considering the variables involved in setting up the required minimal heat balance required in the second step of this process, it might be assumed that the most favorable conditions of operation would require the addition of the solid particles at a relatively low temperature, for example, at room temperature. I have found, however, that this is not the case. It is desirable to add the solid particles to the casting mixture while they are at an elevated temperature and use the large proportion of the solid particles required by Equation I when the particles are at a higher temperature. In any case, it is desirable to use temperature conditions which permit the use of a solid-liquid mixture containing at least 10% by volume of solid particles and, as noted below, I may use as much as 50% by volume of the solid particles.

I prefer to utilize a combination of a super-heated liquid phase and solid particles which are at an elevated

temperature which produces an instantaneous fusion of the surfaces of the solid particles. The use of such a heat balance absolutely guarantees the formation of homogeneous casting. Equation II defines the conditions which will produce instantaneous surface fusion, regardless of the size and population density of the solid particles in the mixture.

Equation II

$$T_s + T_1 \sqrt{\frac{K_1}{K_2}} \geq T_m \left(1 + \sqrt{\frac{K_1}{K_2}} \right)$$

In this equation, T_s , T_1 and T_m have the same meaning as in Equation I. K_1 is the thermal conductivity of the liquid phase and K_2 is the thermal conductivity of the solid phase, both being in terms of B. t. u. per hour, per square foot, per inch, per degree Fahrenheit. In the case of a material, such as, for example, steel, which has a liquid thermal conductivity approximately one-half of its solid thermal conductivity, this equation becomes:

Equation II-A

$$T_s + 0.7T_1 \geq 1.7T_m$$

Equations II and II-A require that the solid phase of the liquid-solid mixture formed in the second step of this method be at a relatively high temperature, i. e. carry a large amount of preheat. However, the relationship expressed by this equation permits the proportion of solid in the liquid-solid mixture to be as high as mechanically convenient. I have found that in the production of casting of regular shapes which have a relative ratio of volume to surface, that I can use solid-liquid mixtures containing as much as 50% by volume of solid particles.

In initial mixtures in the second step of my method in which the solid particles are spherical and constitute less than about fifteen percent by volume of the mixture, the fusion of the surfaces of the spherical particles may be slightly delayed as a consequence of the fact that the flow of heat into a convex surface becomes constricted with the passage of time. In such a system, the incipient fusion of the surfaces of the solid particles is guaranteed if the conditions defined by the following equation are utilized:

Equation III

$$T_1 + T_s \sqrt{\frac{K_1}{K_2}} \geq T_m \sqrt{\frac{K_1}{K_2}}$$

In this equation, the symbols have the same meaning as in Equation II. In a system in which the liquid conductivity is approximately one-half the solid conductivity, this equation becomes:

Equation III-A

$$T_1 + 0.7T_s \geq 1.7T_m$$

Equations III and III-A require somewhat less pre-heat in the solid phase of a given level of super-heat in the liquid phase than Equations II and II-A.

The total heat which must be removed from a casting in the second step of my method when using a heat balance, defined by these equations, is the least when the proportion of solid in the initial solid-liquid mixture is the highest, regardless of how hot the solid is at the time of its introduction into the mixture. For this reason, I prefer to use the highest proportion of hot solid particles or pieces in the mixture that is mechanically convenient. I have found that the most desirable form of solid particles for working at a high solid-liquid ratio is a small sphere. Thus, in the casting of, for example, steel, I prefer to produce a steel shot in the first step of my method which has a diameter falling within the range of about 0.05 inch to about 0.5 inch and not more than one-tenth the smallest dimension of the casting, and use it in the second step of the method while still quite hot.

The method of this invention is particularly valuable when carried out in a continuous manner. In this opera-

tion, it is particularly desirable to carry the second step in a continuous manner, and I prefer to carry out both the first and second steps in a continuous manner. For example, I may continuously produce steel shot by dropping the metal through a non-oxidizing atmosphere of, for example, water gas, producer gas or flue gas in a shot tower and continuously convey the hot shot from the bottom of the shot tower to the top of a mold designed for continuous operation. The casting operation which I use in this operation may be any one of the several types which have heretofore been developed for this purpose.

By such continuous operation of both steps of the method, I am able to utilize the heat contained in the shot as cast and thereby obtain high thermal efficiency in my method. The use of a non-oxidizing and otherwise non-reactive atmosphere in the shot tower enables me to retain complete control over the composition of the casting produced.

The hot shot and molten metal are simultaneously and continuously fed to the top of the continuous mold at a rate which keeps the level of the solid-liquid mixture substantially constant, i. e. the combined rate of feed of the solid shot and the liquid metal is adjusted to equal the rate at which the solid ingot is withdrawn from the mold. The ratio between the rate at which the hot metal shot and the rate at which the molten metal is fed to the top of the mold is adjusted in terms of their respective temperatures upon entering the mold. This adjustment is made by the use of the Equation I and preferably also Equation II-A given hereinbefore.

The time required for a given cross-section of a steel ingot to completely solidify is proportioned to:

Formula A

$$1-f \frac{[0.16(T_1-T_s)+126]}{[0.16(T_1-T_m)+126]}$$

Where f is the fraction of the solid steel shot being fed to the mold, T_1 is the temperature of the molten steel, T_s is the temperature of the shot, 0.16 is the specific heat of steel and 126 is the heat of fusion of the steel.

It will be observed that according to Formula A, when the fraction of solid particles in the mold, represented by f is zero, that the formula becomes unity and that:

$$f \frac{[0.16(T_1-T_s)+126]}{[0.16(T_1-T_m)+126]}$$

is the fractional reduction in the time of solidification of the ingot.

While this formula is concerned only with the solidification of a steel casting, it can be made applicable to the solidification of any given material merely by the substitution of the specific heat and the heat of fusion for the corresponding values for steel (0.16 and 126, respectively) in the formula. Thus, for such general application this formula becomes:

$$f \frac{[\alpha(T_1-T_s)+\beta]}{[\alpha(T_1-T_m)+\beta]}$$

when α represents the specific heat and β the heat of fusion of the material being cast.

This formula is applicable to both the static casting and to continuous casting. It is particularly valuable in connection with continuous casting, since it can be used to accurately predict the rates at which an ingot can be withdrawn from any particular mold operating under uniform cooling conditions, when the mold is fed with different solid-liquid mixtures having different heat balances. This use of the formula in this manner is fully illustrated by the specific examples of the use of the method of this invention given hereinafter.

Also, it will be noted that from this formula when the temperatures of the molten metal and of the shot are the same this term becomes simply:

$$(1-f)$$

Operating under such conditions is, of course, impractical, but the more nearly they are approached, the more nearly the time of solidification becomes directly proportional to the fraction of liquid metal poured into the mold.

Further, it will be noted that according to Formula A a decrease in the amount of shot fed or an increase in its temperature increases the time required for the ingot to freeze. As already noted, I prefer to use a proportion of solid particles at or near the maximum which is mechanically convenient and I have found that I can use as much as 50% by volume. I prefer to use a proportion of solid particles within the range of about 20% to about 50% by volume of the solid-liquid mixture being cast when operating under the temperature conditions defined by Equations II and II-A. Also, I prefer to use the solid particles at the lowest elevated temperature permitted by the relationship defined by Equation II or in the case of Steel Equation II-A. In this manner, I shorten the time required for the ingot to solidify as much as possible while avoiding any risk of producing a non-homogeneous ingot.

The conditions under which the second step of this method may be carried out and the savings in time required in the solidification of a casting are illustrated by the following examples:

Example I

In a casting operation in which a steel melting at 2650° F. is poured at 3000° F. and steel shot having a temperature of 100° F. is admixed therewith in the second step of my method, the maximum percentage of shot which can be included in the mixture, according to Equation I is:

$$(1-f)3000+100f=2650$$

$$f=12\%$$

The use of 12% of shot in the casting operation reduces the time, according to Formula A as follows:

$$1-0.12 \frac{[0.16(3000-100)+126]}{[0.16(3000-2650)+126]}=1-0.384$$

Thus, the time required for solidification is reduced by 38.4%.

Example II

If, instead of using steel shot at 100° F. as in Example I, shot at 1000° F. is added to the casting mixture, the maximum percentage of shot which can be included in the mixture is:

$$(1-f)3000+1000f=2650$$

$$f=17.5\%$$

The use of 17.5% of shot in the casting mixture reduces the time required for the solidification of the casting as follows:

$$1-0.175 \frac{[0.16(3000-1000)+126]}{[0.16(3000-2650)+126]}=1-0.429$$

Thus, the reduction in the solidification time is 42.9%.

Example III

When shot at 2000° F. is used while proceeding otherwise as in Example I, the maximum percentage of shot which may be used is:

$$(1-f)3000+2000f=2650$$

$$f=35\%$$

The reduction in the solidification time in the casting operation according to Formula A is:

$$1-0.35 \frac{[0.16(3000-2000)+126]}{[0.16(3000-2650)+126]}=1-0.55$$

Thus, the reduction in the solidification time is 55%.

Example IV

In a casting operation in which steel melting at 2650° F. is poured at 3000° F. and the maximum quantity of

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shot which can be conveniently added is used, the minimum temperature at which the shot can be added, according to Equation II-A is:

$$T_s = 1.7 \times 2650 - 0.7 \times 3000$$

$$T_s = 2405^\circ \text{ F.}$$

When using shot at 2405° F., the maximum quantity of shot which can be added to the mixture is:

$$3000(1-f) + 2405f = 2650$$

$$f = 59\%$$

Thus, a greater quantity of shot can be used from the standpoint of the heat balance involved, than is ordinarily feasible from a mechanical standpoint. However, if 50% of shot at a temperature of 2405° F. is used, the reduction in the casting time is as follows:

$$1 - 0.5 \frac{[0.16(3000 - 2405) + 126]}{[0.16(3000 - 2650) + 126]} = 1 - 0.61$$

Thus, the reduction in the casting time is cut by 61% when using 50% of shot in the casting mixture.

Example V

If the pouring temperature of the molten metal in Example IV is reduced to 2900° F., and 50% by volume of shot added to the mixture, the minimum temperature at which the shot can be added according to Equation II-A is:

$$T_s = 1.7 \times 2650 - 0.7 \times 2900$$

$$T_s = 2475^\circ \text{ F.}$$

The saving in the solidification time is:

$$1 - 0.5 \frac{[0.16(2900 - 2475) + 126]}{[0.16(2900 - 2650) + 126]} = 1 - 0.62$$

Thus, the reduction in the casting time is 62%. The maximum quantity of shot which can be used from the standpoint of the heat balance is:

$$2900(1-f) + 2475f = 2650$$

$$f = 58\%$$

The use of a larger quantity of shot makes further reduction in the time required for the solidification of the casting.

Example VI

In a casting operation in which steel melting at 2650° F. is poured at 3000° F. and 12% by volume of steel shot is admixed therewith, according to Equation III-A, the temperature of the shot must be at least:

$$T_s = \frac{1.7 \times 2650 - 3000}{0.7}$$

$$T_s = 2140^\circ \text{ F.}$$

The reduction in solidification time under these conditions is:

$$1 - 0.12 \frac{[0.16(3000 - 2140) + 126]}{[0.16(3000 - 2650) + 126]} = 1 - 0.17$$

Thus, the savings in the time of solidification is 17% under these conditions of operation.

Each of the foregoing examples illustrates the casting of a steel having a melting point of 2650° F. for the purpose of giving an accurate comparison of the result obtained by varying operating conditions in accordance with this invention. As clearly brought out by these examples, very substantial reductions can be made in the time required for the solidification of a casting. Thus, the addition of 12% of shot having a temperature of 2140° F. reduces the time required to produce a casting by 17% (Example VI), while the addition of the same amount having a temperature of 100° F. produced a reduction of 38% in the casting time (Example I). Thus, the saving in the casting time increases, as the temperature of the shot is decreased, when the amount of shot used remains constant. How-

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ever, as shown by the comparable Examples I, II and III following the requirements of Equation I, the maximal amount of shot increases as the amount of pre-heat which it carries is increased, and the savings in casting time increases. Thus, these examples give the following comparable results:

Example	Shot Temperature, ° F.	Maximal Volume, percent	Reduction in Casting Time, percent
I.....	100	12.0	38.4
II.....	1,000	17.5	42.9
III.....	2,000	35.0	55.0

Examples IV and V illustrate casting under the conditions required by Equation II and II-A, which permit the use of quantities higher than can normally be used from a mechanical standpoint, give the following comparable results:

Example	Shot Temperature, ° F.	Volume of Shot Used, percent	Maximal Volume of Shot Possible, percent	Reduction in Casting Time, percent
IV.....	2,405	50.0	59.0	61.0
V.....	2,475	50.0	58.0	62.0

Thus, even greater reductions in the time required for the solidification of a casting are obtained by operating under these conditions than under the conditions imposed solely by Equation I. It is for this reason that I prefer to use the conditions required by Equation II and II-A, as well as to use conditions within the essential requirements of Equation I.

These examples show that the time required for solidification of a casting can be reduced by more than 60%. Such a reduction in the time required for the solidification of a casting is of considerable value in batch-wise casting operations, and is of great value in continuous casting operations. As mentioned hereinbefore, the economic efficiency of any casting operation is determined by the amount of the cast material produced per unit of time. In any given casting apparatus, the quantity of the cast material produced per unit of time is controlled by the time required for the casting to solidify. The economic importance of reducing this solidification time by as much as 60% is obvious.

The reduction in the solidification time in the production of castings is only one of the several advantageous features of this method. It reduces the quantity of heat that must be removed in the final casting operation, characterized as the second step of this method, in the exact proportion that it reduces the time required for the solidification of the casting. This feature of the invention is of importance in all types of casting and is particularly important in continuous casting operations in which the rapid removal of heat is a major problem. This feature is of particular importance in the casting of the ferrous metals which have high liquid and solidus temperatures.

Another advantageous feature of this invention is the fact that the solid phase of the liquid-solid mixture which is cast in its second step absorbs heat at points remote from the outer surface of the casting. The heat which is absorbed in this manner does not have to travel to the surface of the embryo casting and pass through the thermal barriers which have been described hereinbefore. This feature is important in the casting of all fusible materials, but becomes of particular importance in the casting of ferrous metals due to their relatively low thermal conductivity and high heat content when in the fused state.

The solid particles in the solid-liquid mixture which is cast in this method form centers of crystallization or solidification in the interior of the embryo casting due both

to their crystal "seeding" action in the melt and the fact that they are absorbing heat from the adjacent liquid phase. This behavior tends to eliminate or minimize many of the difficulties and problems which have heretofore been encountered in casting operations. It more or less completely eliminates the difficulties encountered because of the segregation of impurities and the formation of voids in the center of castings produced by the usual casting methods. Furthermore, it prevents the dendritic crystal growth which is a frequent difficulty in the casting of metals and usually causes the metals to form a fine grain structure which is almost always more desirable than the coarse grain structure formed by the conventional casting operations.

This solidification or crystallization in the interior of embryo casting largely eliminates or definitely minimizes the difficulties heretofore arising in continuous casting operations from the initial formation of a thin skin around the outside of the embryo casting and its remelting and re-solidification. This internal solidification of the embryo casting tends to eliminate the formation of the inverted cone of liquid metal in the top of the casting, and largely eliminates or at least definitely reduces the hydraulic head created by this liquid metal which is so often responsible for the jamming of ingots in the mold and the drainage of the casting to leave a hollow shell when a break-through occurs after the casting has emerged from the mold. These are additional features of this invention which are of particular importance in the casting of the ferrous metals which have a mushy range between their liquidus and solidus temperatures.

The difficulties arising from the peripheral segregation of slag in the continuous casting of ferrous metals have been described hereinbefore. Any slag present in solid particles of the solid-liquid mixture cast by this method cannot segregate when a heat balance is used which permits only an incipient surface fusion of the solid particles, and the presence of the solid particles prevents an agglomeration of slag in the liquid phase. In the alternative in which a heat balance is utilized which causes a more or less complete re-fusion of the solid particles, the temperature of the melt has dropped with a consequent decrease in the time required for the complete solidification of the melt which retards or prevents the agglomeration of masses of slag and their segregation in the surface of the casting.

From the foregoing, it will be appreciated that the method in accordance with this invention minimizes or completely eliminates numerous difficulties which have heretofore been inherent in the casting of ferrous metals. As a result, the use of this method in the continuous casting of ferrous metals makes such casting both practical and economically feasible.

It will be understood that the foregoing examples are presented solely for the purposes of illustration, and it will be fully understood that the scope of this invention is by no means limited to these examples. Many changes can be made in the conditions utilized in the casting of the particular steel cast in the examples and all ferrous and non-ferrous metals may be advantageously cast by this method. Thus, the foregoing description is predicated on the use of a solid and a liquid phase in the second step of my method, which are identical in composition, and homogeneity of composition in the final casting is usually an objective in the method. However, as will be fully understood by those skilled in the art, in the case of carbon steel, for example, a complete uniformity in composition is not always necessary in a casting and the carbon of the steel is capable of solid diffusion. Therefore, it is not always necessary in carrying out this invention to have an exact correspondence between the liquid and solid phases. However, major differences in composition between the solid and liquid phases are

to be avoided, since they defeat the objective of more or less complete casting homogeneity.

It will also be understood that this method of casting is useful in the casting of non-metallic materials, as well as the various metals. Again, it will be understood that many of the details described in the foregoing are for the purpose of fully explaining the nature and advantages of this invention, and it will be obvious to those skilled in the casting arts that many changes and variations can be made in the details of this method, without departing from the spirit of my invention or the scope of the following claims.

What I claim and desire to protect by Letters Patent is:

1. A method for the casting of a fusible material which has a higher density in its solid phase than in its liquid phase, which comprises solidifying in the form of discrete, solid particles at least 10%, by volume of the fused material required to form the desired casting not in excess of that which can be mixed with the remainder of the fused material to produce a solid-liquid mixture which will accurately conform to the inner surface of a casting mold, mixing the solid particles while they are at a temperature above normal atmospheric temperature but below their fusion temperature, with the remainder of the material, while said material is at a temperature above its fusion temperature in a mold to form a solid-liquid mixture which carries a total amount of heat which will cause at least incipient fusion of the surfaces of solid particles of the mixture, and withdrawing heat from the mixture to cause it to solidify.

2. A method for the casting of a fusible material which has a higher density in its solid phase than in its liquid phase which comprises solidifying, in the form of a plurality of discrete particles having a compact form and a largest dimension not larger than one-tenth the smallest cross-sectional dimension being produced and not smaller than a size which provides a mass which will overcome the surface tension of the fused material when the particle is gently deposited thereon, at least 10% by volume of the said fused material and not in excess of that which can be mixed as discrete, solid particles with the liquid portion to form a mixture which will accurately conform to the inner surface of a continuous mold; mixing the solid particles at a temperature above normal atmospheric temperature but below their fusing temperature with the fused material at a temperature above its fusion temperature in a mold, the said temperatures of the solid and liquid phases being selected in terms of fusion temperature of the material being cast and the proportion of solid material present in the said mixture to satisfy the requirements of the equation:

$$(1-f)T_1 + fT_s \geq T_m$$

in which f is the fraction of the solid phase in the liquid-solid mixture, T_1 is the temperature of the fused material entering the mixture, T_s is the temperature of the solid particles entering the mixture and T_m is the fusing temperature of the material; and withdrawing heat from the said mixture.

3. A method for the casting of a metal which comprises solidifying, in the form of a plurality of discrete particles having a compact form and a largest dimension not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than a size which provides a mass which will overcome the surface tension of the fused metal when the particle is gently deposited thereon, a proportion within the range of about 10% by volume to about 50% by volume of the total quantity of a fused material to be used in the formation of a single casting; mixing in a casting mold the solid particles while at a temperature above normal atmospheric temperature, but below their fusing temperature with the fused material while it is at a temperature above its fusion temperature, the said temperatures of

the solid and liquid phases being selected in terms of fusion temperature of the material being cast and the proportion of solid material present in the said mixture to satisfy the requirements of the equation:

$$(1-f)T_1 + fT_s \geq T_m$$

in which f is the fraction of the solid phase in the liquid-solid mixture, T_1 is the temperature of the fused material entering the mixture, T_s is the temperature of the solid particles entering the mixture and T_m is the fusing temperature of the material; and withdrawing heat from the said mixture.

4. A method for the casting of a metal which comprises solidifying, in the form of a plurality of discrete particles having a compact form and a largest dimension not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than a size which provides a mass which will overcome the surface tension of the fused metal when gently deposited thereon, a fraction of the fused metal of at least 10%, by volume, which fulfills the requirements of the equation:

$$(1-f)T_1 + fT_s \geq T_m$$

in which f is the fraction of the solid phase in the liquid-solid mixture, T_m is the fusing temperature of the metal and T_1 and T_s are the temperatures of the liquid metal and of the solid particles, respectively, at which they are to be mixed in a casting mold and which is not in excess of that which can be mixed in the form of the said solid particles with the still liquid portion to form a mixture which will accurately conform to the inner surface of the casting mold; mixing the said particles in a casting mold with the remainder of the fused metal while the particles are at a temperature above normal atmospheric temperature, but below their fusion temperature at least as high and the fused metal is at a temperature no higher than the respective temperatures used in determining the fraction of the metal to be solidified to fulfill the requirements of the said equation; and withdrawing heat from the said mixture to produce a solid, homogeneous casting.

5. A method for the casting of a metal which comprises solidifying, in the form of a plurality of discrete particles having a compact form and a largest dimension not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than a size which provides a mass which will overcome the surface tension of the fused metal when gently deposited thereon, a fraction of the fused metal of at least 10%, by volume, which fulfills the requirements of the equation:

$$(1-f)T_1 + fT_s \geq T_m$$

in which f is the fraction of the solid phase in the liquid-solid mixture, T_m is the fusing temperature of the metal and T_1 and T_s are the temperatures of the liquid metal and of the solid particles, respectively, at which they are to be mixed in a casting mold, and which is not in excess of that which can be mixed in the form of the said solid particles with the still liquid portion to form a mixture which will accurately conform to the inner surface of the mold; mixing in a casting mold the said particles with the remainder of the fused metal while the particles are at a temperature above normal atmospheric temperature at least as high and the fused metal is at a temperature higher than the respective temperatures which were used in determining the fraction of the metal to be solidified to fulfill the requirements of the said equation and the said solid particles are at a temperature which meets the requirements of the equation:

$$T_s + T_1 \sqrt{\frac{K_1}{K_2}} \geq T_m \left(1 + \sqrt{\frac{K_1}{K_2}} \right)$$

in which T_s , T_1 and T_m have the same meanings as in the first stated equation and in which K_1 and K_2 are the thermal conductivities of the liquid and the solid phases,

respectively, of the mixture, and withdrawing heat from the said mixture to produce a solid, homogeneous casting.

6. A method for the casting of a metal which comprises solidifying, in the form of a plurality of discrete particles having a compact form and a largest dimension not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than a size which provides a mass which will overcome the surface tension of the fused metal when gently deposited thereon, a fraction of the fused metal within the range of from about 20% by volume to the maximum amount which can be mixed with the remaining portion of the fused metal to produce a solid-liquid mixture which will accurately conform to the internal surfaces of a casting mold; mixing the said solid particles with the remainder of the fused metal while the said solid particles are at an elevated temperature below their melting point, and the said liquid metal is at a temperature above its fusion temperature and the said temperatures, respectively, fulfill the requirements of the equation:

$$T_s + T_1 \sqrt{\frac{K_1}{K_2}} \geq T_m \left(1 + \sqrt{\frac{K_1}{K_2}} \right)$$

in which T_s , T_1 and T_m have the same meaning as in the first stated equation and in which K_1 and K_2 are the thermal conductivities of the liquid and the solid phases, respectively, of the mixture; and withdrawing heat from the said mixture to produce a solid, homogeneous casting.

7. A continuous method for the casting of a fusible material which has a higher density in its solid phase than in its liquid phase, which comprises solidifying in the form of a plurality of discrete particles a portion of the fused material required to form the desired casting of at least 10% by volume and not in excess of that which can be mixed with the remainder of the fused material to produce a solid-liquid mixture which will accurately conform to the inner surface of a continuous casting mold; continuously feeding a stream of the molten metal and a stream of the solidified particles while they are at an elevated temperature below their melting point to a continuous casting mold at individual rates which are proportional to division of the original fused material to solidify one portion thereof and at a combined rate of feed which furnishes the solid-liquid mixture to the mold at the same rate at which a casting is continuously withdrawn therefrom, to form a solid-liquid mixture which carries a total amount of heat which will cause at least an incipient fusion of the solid particles of the mixture; continuously withdrawing heat from the mixture to solidify at least the portion of the said solid-liquid mixture adjacent the inner surfaces of the said casting mold; and continuously withdrawing the said casting from the mold.

8. A continuous method for the casting of a fusible material which has a higher density in its solid phase than in its liquid phase; which comprises solidifying in the form of a plurality of substantially spherical particles, a portion of the fused material required to form the desired casting of at least 10%, by volume not in excess of that which can be admixed with the remainder of the fused material to produce a solid-liquid mixture which will accurately conform to the inner surface of a continuous casting mold; continuously feeding a stream of the molten metal and a stream of the spherical particles while they are at an elevated temperature below their melting point to a continuous casting mold at individual rates which are proportional to the division of the fused material to solidify one portion thereof and at a combined rate of feed which furnishes the solid-liquid mixture to the mold at the same rate that a casting is continuously withdrawn therefrom, to produce a solid-liquid mixture which carries a total amount of heat which will cause at least an incipient fusion of the surfaces of the solid particles of the mixture and withdrawing heat from the mixture; continuously withdrawing heat from

the said solid-liquid mixture; and continuously withdrawing a casting from the said mold.

9. A continuous method for the casting of a fusible material which has a higher density in its solid phase than in its liquid phase; which comprises solidifying a portion of the fused material in the form of a plurality of discrete particles having a compact form and a largest dimension not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than a size which provides a mass which will overcome the surface tension of the fused material when the particle is gently deposited thereon, the said portion which is solidified being at least 10%, by volume not in excess of that which can be admixed with the liquid portion to form a mixture which will accurately conform to the inner surface of a continuous mold; continuously feeding a stream of the molten metal and of the discrete particles while they are at an elevated temperature below their melting point to a continuous casting mold at individual rates of feed which are proportional to the division of the fused material to solidify one portion thereof and a combined rate of feed which furnishes the solid-liquid mixture to the mold at the same rate that a casting is continuously withdrawn therefrom, to produce a solid-liquid mixture which carries a total amount of initial heat which will cause at least an incipient fusion of the surfaces of the solid particles of the mixture; continuously withdrawing heat from the solid-liquid mixture; and continuously withdrawing a solidified casting from the mold at a rate correlated with the rate of the solidification of the said solid-liquid mixture as controlled by the said total heat in the said initial solid-liquid mixtures and the relative proportions of solid and liquid in the said mixture.

10. A continuous method for the casting of fused metal which comprises solidifying a portion of the fused metal in the form of a plurality of discrete particles having a compact form and a largest dimension not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than that which will provide a mass which will overcome the surface tension of the fused material when the particle is gently deposited thereon, the said portion of the metal being solidified being at least 10%, by volume, and not in excess of that which can be mixed with the remaining portion of the metal to produce a solid-liquid mixture which will accurately conform to the inner surface of a continuous casting mold; continuously feeding a superheated stream of the molten metal and a stream of the solid particles, having a temperature above normal atmospheric temperature but below their fusion temperature, to a continuous casting mold at individual rates of feed which are proportional to the division of the fused metal to solidify one portion thereof and at a combined rate of feed which furnishes the solid-liquid mixture to the mold at the same rate that a casting is continuously withdrawn therefrom, to produce a solid-liquid mixture which carries a total initial heat content which will cause at least an incipient fusion of the surfaces of the solid particles of the mixture; continuously withdrawing heat from the solid-liquid mixture; and continuously withdrawing a solidified casting from the mold at a rate correlated with the rate of solidification of the said solid-liquid mixture as controlled by the fusing temperature of the metal, the temperatures of the molten and solid phases in the initial mixture and the relative proportions of the two phases therein.

11. A continuous method for the casting of fused metal which comprises solidifying a portion of the fused metal in the form of a plurality of discrete particles having a compact form and a largest dimension not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than that which will provide a mass which will overcome the surface tension of the fused material when the particle is gently

deposited thereon, the said portion of the metal which is being solidified being at least 10%, by volume, and not in excess of that which can be mixed with the remaining portion of the metal to produce a solid-liquid mixture which will accurately conform to the inner surface of a continuous casting mold; continuously feeding a superheated stream of the molten metal and a stream of the solid particles having a temperature above normal atmospheric temperature, but below their fusion temperature, to a continuous casting mold at individual rates of feed which are proportional to the initial division of the fused metal to solidify one portion thereof and at a combined rate of feed which furnishes the solid-liquid mixture to the mold at the same rate that a casting is continuously withdrawn therefrom, while the solid particles are at an elevated temperature below their fusion temperature and the liquid metal is at a temperature above its fusion temperature, which temperatures satisfy the requirements of the equation:

$$(1-f)T_1 + fT_s \geq T_m$$

in which f is the fraction of the solid phase in the liquid-solid mixture, T_1 is the temperature of the fused material entering the mixture, T_s is the temperature of the solid particles entering the mixture and T_m is the fusing temperature of the metal, continuously withdrawing heat from the said solid-liquid mixture and continuously withdrawing a solidified casting from the mold at a rate correlated with the rate of solidification of the said solid-liquid mixture as controlled by the total heat in the initial solid-liquid mixture and the relative proportions of solid and liquid in the said mixture.

12. A continuous method for the casting of a fused metal which comprises solidifying in the form of a plurality of spherical particles having a diameter not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than that which will provide a mass which will overcome the surface tension of the fused material when the particle is gently deposited thereon, a fraction of the fused metal of at least 10%, by volume, which fulfills the requirements of the equation:

$$(1-f)T_1 + fT_s \geq T_m$$

in which f is the fraction of the solid phase in the liquid-solid mixture, T_m is the fusing temperature of the metal and T_1 and T_s are the temperatures of the liquid metal and of the solid particles, respectively, at which they are to be mixed in a continuous casting mold, and which is not in excess of the proportion which can be mixed in the form of the said solid particles with the still liquid portion to form a mixture which will accurately conform to the inner surface of a continuous mold; continuously feeding a stream of the molten metal and of the spherical particles to a continuous mold while the particles and the molten metal are, respectively, at the temperatures used in determining the fraction of the metal to be solidified to fulfill the requirements of the said equation and while the temperature of the said particles is above normal atmospheric temperature, but below their melting point and fulfills the requirements of the equation:

$$T_s + T_1 \sqrt{\frac{K_1}{K_2}} \geq T_m \left(1 \sqrt{\frac{K_1}{K_2}} \right)$$

in which T_s , T_1 and T_m have the same meanings as in the first stated equation and in which K_1 and K_2 are the thermal conductivities of the liquid and the solid phases, respectively, of the mixture; continuously withdrawing heat from the said metal; and continuously withdrawing a solidified casting from the said continuous casting mold at a rate correlated with the rate of solidification of the said solid-liquid mixture as controlled by the total heat in the initial solid-liquid mixture and the relative proportions of solid and liquid in the said mixture.

13. A method for the continuous casting of a fused ferrous metal which comprises solidifying, in the form of

a plurality of spherical particles having a diameter not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than that which will provide a mass which will overcome the surface tension of the fused material when a particle is gently deposited thereon, a fraction of the fused metal of at least 10%, by volume which fulfills the requirements of the equation:

$$(1-f)T_1 + fT_s \geq T_m$$

in which f is the fraction of the solid phase in the liquid-solid mixture, T_m is the fusing temperature of the metal and T_1 and T_s are the temperatures of the liquid metal and of the solid particles, respectively, at which they are to be mixed in a continuous casting mold, and which is not in excess of the proportion which can be mixed with the still liquid portion of the metal to form a mixture which will accurately conform to the inner surface of a continuous mold; continuously feeding a stream of molten metal and of the spherical particles to a continuous casting mold while the particles are above normal atmospheric temperature, but below their fusion temperature and the temperatures of the particles and the molten metal are, respectively, at the temperatures used in determining the fraction of the metal to be solidified to fulfill requirements of the said equation; continuously withdrawing heat from the said metal; and continuously withdrawing a solidified casting from the said continuous casting mold at a rate correlated with the rate of solidification of the said solid-liquid mixture as controlled by the total heat in the initial solid-liquid mixture and the relative proportions of solid and liquid in the said mixture.

14. A method for the continuous casting of a fused ferrous metal which comprises solidifying in the form of a plurality of substantially spherical particles having a diameter not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than that which will provide a mass which will overcome the surface tension of the fused material when a particle is gently deposited thereon, a fraction of the fused metal of at least 10%, by volume which fulfills the requirements of the equation:

$$(1-f)T_1 + fT_s \geq T_m$$

in which f is the fraction of the solid phase in the liquid-solid mixture, T_m is the fusing temperature of the metal and T_1 and T_s are the temperatures of the liquid metal and of the solid particles, respectively, at which they are to be mixed in a continuous casting mold, and which is not in excess of that which can be mixed with the still liquid portion of the metal to form a mixture which will accurately conform to the inner surface of a continuous mold; continuously feeding a stream of molten metal and of the spherical particles to a continuous mold while the temperatures of the particles and the molten metal are, respectively, at the temperatures used in determining the fraction of the metal to be solidified to fulfill the requirements of the said equation and the said solid particles are at a temperature above normal atmospheric temperature, but below their fusion temperature, which meets the requirements of the equation:

$$T_s + 0.7T_1 \geq 1.7T_m$$

in which T_s , T_1 and T_m have the same meaning as in the first stated equation; and continuously withdrawing a solidified casting from the said continuous casting mold at a rate correlated with the rate of solidification of the said solid-liquid mixture as controlled by the total heat in the initial solid-liquid mixture and the relative proportions of solid and liquid in the said mixture.

15. A method for the continuous casting of a fused ferrous metal which comprises; solidifying in the form of a plurality of spherical particles having a diameter not larger than one-tenth the smallest cross-sectional dimension of the casting being produced and not smaller than that which will provide a mass which will overcome the surface tension of the fused material when a particle is gently deposited thereon, a fraction of the fused metal of at least 10%, by volume, which fulfills the requirements of the equation:

$$(1-f)T_1 + fT_s \geq T_m$$

in which f is the fraction of the solid phase in the liquid-solid mixture, T_m is the fusing temperature of the metal and T_1 and T_s are the temperatures of the liquid metal and of the solid particles, respectively, at which they are to be mixed in a continuous casting mold, and which is not in excess of that which can be mixed with the still liquid portion of the metal to form a mixture which will accurately conform to the inner surface of the continuous casting mold; continuously feeding a stream of molten metals and of the spherical particles to a continuous casting mold while the temperatures of the particles and the molten metal are, respectively, at the temperatures used in determining the fraction of the metal to be solidified to fulfill the requirements of the said equation and the said solid particles are at a temperature above normal atmospheric temperature, but below their fusion temperature which meets the requirements of the equation:

$$T_s + 0.7T_1 \geq 1.7T_m$$

in which T_s , T_1 and T_m have the same meaning as in the first stated equation; and continuously withdrawing a solidified casting from the mold at a rate correlated with the rate of solidification of the said solid-liquid mixture as determined by the formula:

$$1 - f = \frac{0.16(T_1 - T_s + 126)}{0.16(T_1 - T_m + 126)}$$

in which f , T_s , T_1 and T_m have the same meanings as in the first stated equation and 1 represents the rate of withdrawal from the casting mold of an ingot produced solely from molten metal which is introduced into the mold at the temperature T_1 with an identical rate of cooling of the casting mold.

References Cited in the file of this patent

UNITED STATES PATENTS

6,460	Smith	May 22, 1849
20,250	Booth	May 18, 1858
2,294,170	Francis et al.	Aug. 25, 1942
2,574,357	Stammer et al.	Nov. 6, 1951

FOREIGN PATENTS

104,675	Australia	Aug. 11, 1938
505,427	Great Britain	May 1, 1939
755,073	France	Sept. 4, 1933