METHOD FOR CONTINUOUSLY CASTING STEEL BILLET STRANDS TO MINIMIZE THE POROSITY AND CHEMICAL SEGREATION ALONG THE CENTER LINE OF THE STRAND

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Porosity and chemical segregation along the center line of a continuously cast steel billet strand are minimized by controlling the cooling and solidification of the continuously cast strand in such fashion that the central region solidifies in a vertical freezing mode. The transverse freezing which proceeds from the skin inward is retarded until such time as the temperature of the molten central region favors vertical solidification, whereafter the billet strand is further cooled to allow completion of its solidification in the vertical mode.

22 Claims, 5 Drawing Figures
FIG. 1 PRIOR ART

CENTER LINE

\[ \sigma = 0.042\% \]
\[ \Delta = 0.060\% \]

5/16" OFF CENTER LINE

\[ \sigma = 0.015\% \]
\[ \Delta = -0.020\% \]

A BILLE CAST VERY HOT

OUTSIDE CENTER

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FIG. 2

\[ \% C \]

\[ \text{CENTER LINE} \]
\[ \sigma = 0.016\% \]
\[ \Delta = -0.012\% \]

\[ \text{BILLET LENGTH''} \]

\[ \frac{5}{16}\text{'' OFF CENTER LINE} \]
\[ \sigma = 0.011\% \]
\[ \Delta = -0.01\% \]

\[ \text{BILLET LENGTH''} \]

\[ \text{A BILLET CAST COLD} \]

\[ \text{MEAN CONTENTS FOR EACH POSITION} \]

\[ \text{OUTSIDE CENTER} \]

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FIG. 3

TUNDISH NOZZLE

MOLD

SPRAY CHAMBER

MUFFLE FURNACE

PRIMARY COOLING

FAST COOLING ZONE USING WATER SPRAYS

SLOW COOLING ZONE USING MUFFLE FURNACE

ACCELERATED COOLING ZONE USING RADIANT COOLING

SOLID BILLET SKIN

LIQUID BILLET CENTER

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FIG. 4

TUNDISH LIQUID STEEL

STEEL STREAM LIQUID ARGON

COPPER MOLD

WATER JACKET

SPRAY COOLING

WATER IN

STEEL BILLET

SOLID SKIN

LIQUID CENTER

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BY
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METHOD FOR CONTINUOUSLY CASTING STEEL BILLET STRANDS TO MINIMIZE THE POROSITY AND CHEMICAL SEGREGATION ALONG THE CENTER LINE OF THE STRAND

BACKGROUND OF THE INVENTION

Continuous or direct strand casting of non-ferrous metals has been an established technique for many years and, more recently, these techniques in general have been extended to the continuous casting of steel. The process in general involves pouring the liquid steel from a ladle into an intermediate container or tundish from which the molten metal is continuously delivered to bottomless molds at a suitable casting rate established by the tundish nozzle opening, the metal properties, the metal pressure above the nozzle and the setting of any flow control devices if used. In the mold, the metal solidifies from the outside inwardly so as to form a solid skin near the mold walls and to build it up progressively by freezing inwardly, the skin thickness being sufficient as the billet or strand is being withdrawn through the lower end of the mold so as to withstand the metallurgical head of the molten interior of the billet strand. As the strand descends continuously the molten steel in the center eventually freezes whereafter the solidified billet strand may be cut into lengths and subsequently processed in conventional fashion.

Due to the relatively poor heat conductivity and high melting point of steel, the billet freezing process described above requires a relatively long period of time. As a result, segregation of chemical elements may be quite pronounced in the solidified billet due to the fact that, during freezing, the still liquid inner portion of the billet becomes enriched in these dissolved elements compared to the already solidified crystals of iron forming the outer portion of the billet. The result of this steady enrichment of the liquid portion in a solidifying billet strand is a relatively high concentration of the elements such as carbon, manganese, chromium, sulfur, etc. within the pools of liquid steel which are last to solidify. Thus, analysis of a continuously cast steel billet strand often shows variable concentrations of chemical elements in the region of and along the billet axis which may result in measurable changes from point to point in the mechanical properties of the metal and in its response to heat treatment and to cold forming. These effects can result in severe restrictions to the use to which products made out of the continuously cast steel billets may be put.

The above-mentioned chemical segregation is a phenomenon which is also encountered in more conventional ingot casting and so various conventional techniques, for example strongly tapered molds and hot tops, have been developed in ingot casting practice to avoid or minimize the chemical segregation and/or porosity which might otherwise be objectionable. These ingot casting techniques are either impossible or impractical in connection with continuously casting steel billet strands. Moreover, the chemical segregation as discussed above is a more serious problem in continuously cast steel billet strands as much as continuously cast ingots have a very much smaller original cross-sectional area than ingots. As a consequence, the high degree of hot working is usually practiced in conjunction with ingots and which is capable of dispersing some of the segregated material due to the large reduction in cross section of the ingot from its original size to the finished product makes the segregation problem much less critical in ingots since the high degree of hot working will elongate, break up and otherwise disperse the segregations where they occur.

Since the continuously cast billets are of relatively small cross section, they will not be reduced drastically in cross-sectional area by subsequent hot working and the chemical segregations which may be present cannot be much reduced in cross section, elongated, and broken up so as to minimize their effect as is possible with ingot castings.

SUMMARY OF THE INVENTION

Accordingly, it is of primary concern in connection with the present invention to provide a process for minimizing chemical segregation and/or porosity along the center line of a continuously cast steel billet strand, particularly as it relates to the continuous casting of billets having relatively small cross section such as might be of concern in connection with small installations or independent steel producers.

The process according to the present invention involves controlled casting and controlled cooling of the continuously cast billet strands such that the transverse columnar crystal growth which is initiated within the mold by the formation of the billet strand skin is not permitted to progress close to the center line of the billet strand. Instead, the rate of transverse solidification is retarded so as to maintain a molten steel core or central region until such time as the temperature of this molten steel has decreased to that value which allows vertical crystal growth or solidification to overtake the transverse crystal growth and thereby finish or complete the solidification of the center of the strand in the vertical mode. At the same time, the onset of the vertical solidification in the billet center is accelerated by the cooling of the metal stream between the tundish and the mold through the use of chilling additions to the stream such as liquefied gases or finely dispersed steel.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a series of graphs representing chemical segregation associated with a conventionally cast billet strand;

FIG. 2 is a series of graphs similar to FIG. 1 showing the effect of the process according to the present invention;

FIG. 3 is a diagrammatic view illustrating the principle according to the present invention;

FIG. 4 is a largely diagrammatic view illustrating one preferred embodiment of the present invention; and

FIG. 5 is a further view illustrating another preferred embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

A typical longitudinal section of a continuously cast steel billet strand obtained by conventional processing is characterized by the presence of voids along the center line and along which center line chemical segregation is manifest. Also, there is extensive, transverse columnar crystal growth which characterizes conventionally obtained, continuously cast steel billet strands. The uppermost graph in FIG. 1 illustrates the effect of the chemical segregation with respect to carbon content typically obtained along the center line of a billet cast by conventional processes. In this uppermost graph, the
dashed line 10 illustrates the nominal carbon content of the billet as a whole and it will be noted that most of the analyses along the length of the billet center line show a much greater percentage of carbon than the nominal content established by the dashed line 10. Thus, with respect to the lowermost portion of FIG. 1, wherein a diagrammatic illustration of one-half the billet longitudinal section is graphed, the center line as represented by the point 12 displays the means content of an area enriched in carbon. In the second graph illustrated in FIG. 1, the analyses were taken 5/16 of an inch off or laterally of the center line of the billet and these analyses show a net decrease in carbon content as illustrated by the point 14 in the lowermost graph in FIG. 1. Further analyses taken further and further away from the center line toward the outside of the billet illustrate the trends which are typical as illustrated by the points 16, 18, 20 and 22 shown in the lowermost portion of FIG. 1.

This type of situation as is illustrated in FIG. 1 and pertaining both to porosity along the center line of the billet strand and chemical segregation and disparities in chemical analysis particularly at or near the center line of the billet are typical of continuously cast steel billet strands following conventional continuous casting techniques. If the billet cross section is large enough such that the tandish nozzle is also large enough to permit the steel to be cast at or near its liquidus temperature without the possibility of nozzle plugging due to the metal freezing therein, extensive transverse columnar crystal growth of is not encountered and a more acceptable product may be obtained. However, particularly where the billet cross section is small so that the tandish nozzle is also quite small in cross section, the steel must be cast hot to avoid nozzle plugging. By the term “at or near its liquidus temperature” is meant ±30°F with respect to the liquidus temperature whereas casting “hot” will be understood to mean casting from the tandish at a temperature at about 80°-120°F above the liquidus temperature. Casting hot is a practical necessity in connection with billets of small cross section in view of the fact that even though a nozzle of small diameter may not plug theoretically at a casting temperature at or near the liquidus temperature of the steel being cast, neither the analysis of the steel nor the temperature throughout the casting of a heat as well as other factors may be controlled so precisely that plugging cannot occur.

With reference to FIG. 3, if the continuous casting stream 24 issuing from the tandish nozzle 26 is “hot” as defined above and is directed into the continuous casting mold 28 with sufficient mold cooling such that a skin 30 forms around the billet strand, the thickness of this skin as the billet strand emerges from the mold 28 being sufficient to withstand the metallostatic head of molten metal 32 contained by the skin 30, the transverse columnar crystal growth initiated by this skin formation will, in conventional practice, proceed nearly all the way to the center line of the billet, resulting in a billet configuration according to conventional practice. In those situations wherein the steel may be teemed from the tandish at or near the liquidus temperature of the steel, there will be less tendency to produce the conventional type of billet, as noted above. However, according to one aspect of the present invention, the emergent billet strand in either case is subjected to the usual water spray cooling as indicated generally by the reference character 34 in FIG. 3 immediately below the mold 28, but this water spray cooling does not extract as much heat from the billet strand as is conventional, one criterion of the present invention being that the skin formation is caused to progress by virtue of the water spray 34 only to that extent to provide a progressive skin thickening in transverse freezing mode such as is capable of withstanding the metallostatic head of the molten core 32. Thus, the initial spray cooling is controlled to prevent such a rapid rate of transverse crystalline growth as would allow this transverse solidification to take place nearly all the way to the center line of the billet strand. Below this water cooling, there may be provided a muffle furnace zone wherein the cooling rate is further controlled, the muffle furnace being indicated generally by the reference character 36 in FIG. 3 and which serves the purpose of slowing down the rate of cooling of the exterior surface of the billet strand to allow the core 32 to remain liquid until its temperature has decreased to that value at which vertical solidification will be favored, whereafter the accelerated cooling zone 38 is encountered such that ultimately the molten core 32 may complete solidification in the vertical mode as opposed to the conventional transverse mode. The resultant product will display a central region of the billet strand which has frozen in the vertical mode thereby to eliminate the porosity manifest in conventional billets. Further, the chemical segregation characteristics of a billet cast in accord with the showing of FIG. 3 and resulting in a billet configuration according to this invention typically will be in accord with the graphs shown in FIG. 2. The graphs of FIG. 2 are compounded similarly to those explained in conjunction with FIG. 1 and as will be evident upon inspection, the segregation characteristics of steel near the center line are very much less pronounced than the corresponding characteristics as illustrated in FIG. 1. However, in instances where the billet strand is of relatively small cross-sectional area, and therefore must be cast hot, the principles according to the process described in conjunction with FIG. 3 may be insufficient to produce alone the billet configurations according to this invention and a further aspect of the present invention may be required.

This further aspect of the invention involves promoting the onset of vertical solidification by forcibly cooling the tandish-to-mold stream 40 as illustrated in FIG. 4. In FIG. 4, the tandish 42 has a bath 44 of molten steel maintained at a predetermined height therewithin, such steel being at a temperature substantially greater than the liquidus temperature of the molten metal (i.e., at least about 80°F greater) and the stream 40 is forcibly cooled, preferably near its confluence with the body of metal 46 in the mold 48 by directing a continuous stream of liquid argon or other liquid gas against the stream 40 through a suitable conduit or pipe 50 as illustrated. Typically, the liquefied gas will be at its boiling point temperature as conventionally supplied and the amount of liquid gas so introduced will be of that amount sufficient to extract heat from the steel at the point where the body of molten metal 46 will be at or near the liquidus temperature, i.e., plus or minus 30°F with respect to the liquidus temperature of the molten steel. Other inert gases may be utilized or liquid nitrogen may also be utilized whereupon an alloying effect may be obtained. In any event, it is also preferred that the casting apparatus be pro-
vided with a flexible shroud 52 as disclosed, for example, in copending commonly assigned application Ser. No. 745,728 so that the liquid argon or other gas introduced will effectively prevent oxidation of the molten steel due to exposure to the ambient air.

In FIG. 4, the water cooling is effected again in the region indicated by the reference character 54 and, as before, the amount of water introduced in such spray cooling apparatus is significantly less than that which would otherwise be utilized in conventional continuous casting processes, the idea again being to allow the skin to increase in thickness towards the center line of the billet substantially only by that amount which will resist the metallostatic head of the molten steel core and permit the molten steel core to lower its temperature to that temperature which favors vertical solidification so that the exposure of the billet strand below the water spray apparatus 54 will allow, through radiant cooling, the molten core to complete solidification in the vertical mode according to this invention. The muffle furnace 36 in FIG. 3 may in certain designs be omitted as shown in FIG. 4.

Another preferred form of the process is illustrated in FIG. 5 wherein the tundish-to-mold stream 56, being at temperature substantially greater than the liquidus temperature of the molten steel, is cooled by the introduction of a steel wire 58 which has been coated with aluminum. The steel wire is introduced at a rate such that the heat required to bring it to its melting temperature and for its fusion will lower the temperature of the liquid steel to about the liquidus temperature thereof as described hereinbefore and, in this particular case, the aluminum coating on the steel wire is for the purposes of deoxidization. Preferably, the tundish-to-mold stream is protected by an inert atmosphere.

The water spray 60 is utilized in FIG. 5 as is the muffle furnace 62, the last cooling stage as indicated by the reference character 64 being by radiant cooling, the operation and effect of the water spray 60 and muffle furnace 62 being as described hereinbefore in conjunction with FIG. 3. With the apparatus disclosed in FIG. 5, inclusive of the muffle furnace 62, closer control of the crystalline growth characteristics of the billet may be obtained. However, as stated hereinbefore, the muffle furnace 62 may be omitted if desired without sacrificing the principles according to the present invention.

It will further be understood that fine steel wire alone may be introduced in an amount as described hereinbefore or it may be introduced as an alloying agent or, further, either steel alone or steel alloy may be introduced in other forms as for example in the form of fine shot or the like.

In any event, the basic concept according to the present invention is to retard the transverse freezing of the skin which is initiated by the skin formation starting within the mold until the liquid core has had a chance to cool down to that temperature in which further cooling will favor completion of solidification at least in the central region of the core in the vertical mode, while at the same time promoting the onset of the vertical solidification through the chilling of the liquid steel stream after it passed the tundish nozzle by means of liquefied inert gases or finely divided steel like thin wire or shot. The resultant product will be in accord with this invention and will display minimal porosity and chemical segregation as illustrated in that figure and in FIG. 2.

To illustrate practical embodiments of the invention, reference is had to the following:

**EXAMPLE I**

A melt of 1,038 grade steel was cast from a tundish at an average temperature of 2,800°F in the tundish. The tundish nozzles of five-eighth inch diameter discharged the liquid steel into two 4 × 4 × 30 inches water-cooled copper molds at a rate of 120 inches of billet per minute. A stream of liquid argon, capable of absorbing about 2 B.T.U. per pound of steel billet was sprayed onto the flowing liquid steel in the mold space providing thereby sufficient cooling for an early onset of vertical solidification. A secondary cooling was obtained by water spraying discharging only about 70 gallons of water per minute per strand over a length of about 60 inches and below this segment the billet was more slowly cooled simply by radiant cooling. The billets so cast were in conformity with the freezing pattern of this invention and the chemical segregation characteristics of FIG. 2.

**EXAMPLE II**

A steel melt as described in conjunction with Example I was cast as before but the chilling effect of the liquid argon stream was replaced by the progressive introduction of a thin, aluminum coated steel wire which was directed into the shielded space containing the inert gas through a thin tube aimed at the metal stream. The wire was of 0.080 inch diameter and was introduced at a rate of 0.30 per cent of wire to the billet while the aluminum deoxidization was achieved with aluminum coating proportional to 0.005 per cent aluminum with respect to the melt. The water spray discharged from 60 to 80 gallons per minute per strand through four groups of nozzles, each centered on a billet face. Every group comprised three 0.0154 inch and eight 0.0938 inch diameter nozzles. The muffle furnace surrounded the billet strand in each case and extended over a length of about 15 feet, whereafter more rapid cooling of the billet was obtained by radiation loss, all as described in conjunction with FIG. 5.

What is claimed is:

1. In the continuous casting of steel billet strands which involves teeming molten steel from a tundish at a controlled rate into a continuous casting mold wherein a solidified skin is formed on the mold side of the billet strand; and then

   a. controlling heat transfer from the billet strand in the region immediately below said mold to allow progressive increase in thickness of said skin due to transverse solidification of the molten steel contained by said skin only to that extent to provide a progressive skin thickening in transverse freezing mode which is capable of withstanding the metallostatic head of the molten core and which consequently is significantly less than that amount which would favor transverse solidification all the way to the center line of the billet strand;

   b. continuing the controlled cooling of the billet strand in the manner specified in step (a) until the temperature of the billet steel at the center line of the billet strand has decreased to that temperature which favors vertical solidification thereof, and then
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c. cooling the billet strand to complete solidification of its central region in the vertical solidification mode;

the controlled cooling of steps (a) and (b) being effected by water spray applied to the external surface of the billet strand and including the step of cooling the molten steel after it passes through the tundish nozzle and while entering the mold to about its liquidus temperature.

2. In the continuous casting method according to claim 1 wherein the molten steel entering the mold is cooled by vaporization of a liquefied gas.

3. In the continuous casting method according to claim 2 wherein said liquefied gas is argon.

4. In the continuous casting method according to claim 2 wherein said liquefied gas is nitrogen.

5. In the continuous casting method according to claim 1 wherein the molten steel entering the mold is cooled by removal of the heat required to warm up and fuse material introduced into such molten steel.

6. In the continuous casting method according to claim 5 wherein said material is steel.

7. In the continuous casting method according to claim 5 wherein said material includes an alloying constituent for the billet strand.

8. In the continuous casting method according to claim 5 wherein said material is aluminum coated steel wire.

9. In the continuous casting of steel billet strands which involves teeming molten steel from a tundish at a controlled rate into a continuous casting mold wherein a solidified skin is formed on the billet strand and progressively withdrawing such billet strand from the mold, the improvement which comprises the steps of:

a. controlling heat transfer from the billet strand in the region immediately below said mold to allow progressive increase in thickness of said skin due to transverse solidification of the molten steel contained by said skin only to that extent to provide a progressive skin thickening in transverse freezing mode which is capable of withstanding the metallostatic head of the molten core and which consequently is significantly less than that amount which would favor transverse solidification all the way to the center line of the billet strand;

b. continuing the controlled cooling of the billet strand in the manner specified in step (a) until the temperature of the molten steel at the center line of the billet strand has decreased to that temperature which favors vertical solidification thereof; and then

c. cooling the billet strand to complete solidification of its central region in the vertical solidification mode and including the step of cooling the molten steel after it passes through the tundish nozzle and while entering the mold to about its liquidus temperature.

10. In the continuous casting method according to claim 9 wherein the molten steel entering the mold is cooled by vaporization of a liquid gas.

11. In the continuous casting method according to claim 10 wherein said liquid gas is argon.

12. In the continuous casting method according to claim 10 wherein said liquid gas is nitrogen.

13. In the continuous casting of steel billet strands which involves teeming molten steel from a tundish at a controlled rate into a continuous casting mold wherein a solidified skin is formed on the billet strand and progressively withdrawing such billet strand from the mold, the improvement which comprises the steps of:

a. controlling heat transfer from the billet strand in the region immediately below said mold to allow progressive increase in thickness of said skin due to transverse solidification of the molten steel contained by said skin only to that extent to provide a progressive skin thickening in transverse freezing mode which is capable of withstanding the metallostatic head of the molten steel; and then

c. cooling the billet strand to complete solidification of its central region in the vertical solidification mode; and the molten steel entering the mold being cooled by removal of the heat required to warm up and fuse the material introduced into such molten steel.

14. In the continuous casting method according to claim 13 wherein said material is steel.

15. In the continuous casting method according to claim 13 wherein said material includes an alloying constituent for the billet strand.

16. In the continuous casting method according to claim 13 wherein said material is aluminum coated steel wire.

17. The method of continuously casting steel to produce a billet strand of indefinite length with minimal porosity and chemical segregation along the center line of the billet strand, which comprises the steps of:

a. teeming molten steel from a tundish at a temperature sufficiently higher than the liquidus temperature of the steel to insure against plugging of the tundish nozzle, and directing such steel into a continuous casting mold at a controlled rate;

b. cooling the molten steel to about its liquidus temperature as it enters the mold;

c. forming a skin of sufficient thickness around the billet strand with said mold to withstand metallostatic head of molten steel as the billet strand emerges from the mold;

d. controlling the cooling of the emergent billet strand by extracting heat therefrom at a rate only to that extent to provide a progressive skin thickening in transverse freezing mode which is capable of withstanding the metallostatic head of the molten core and which consequently is significantly less than that rate which would favor transverse solidification across the entire cross section of the billet strand whereby the center of the billet strand remains in molten condition, and continuing such controlled cooling until the temperature of molten steel at the center of the billet strand reaches that value which favors vertical solidification thereof; and then
e. radiantly cooling the billet strand to complete solidification of the molten steel at the center of the billet strand in the vertical mode.

18. The method of continuous casting as defined in claim 17 wherein the cooling of step (b) is effected by vaporization of a liquefied gas.

19. The method of continuous casting as defined in claim 18 wherein said liquefied gas is argon.

20. The method of continuous casting as defined in claim 18 wherein said liquefied gas is nitrogen.

21. The method of continuous casting as defined in claim 17 wherein the cooling of step (b) is effected by introducing fine steel wire into the tundish-to-mold stream.

22. The method of continuous casting as defined in claim 21 wherein said steel wire is coated with aluminum.