CONTINUOUSLY CAST STEEL SLABS AND METHOD OF MAKING SAME

John N. Hornak, Munhall, Pa., assignor to United States Steel Corporation, a corporation of Delaware
 Filed Aug. 25, 1966, Ser. No. 574,997

Int. Cl. C22c 7/10; C22c 39/04; B22d 11/00

U.S. Cl. 75—49

5 Claims

ABSTRACT OF THE DISCLOSURE

A method of producing steel suitable for use in sheets and tin plate in a continuous-casting process. A steel free of blowholes in the as-cast condition and containing a controlled quantity and size of silicate inclusions is required. This necessitates lowering the total oxygen content of the steel to about 150 parts per million. The invention accomplishes this by adding a small quantity of silicon to the steel in the tap ladle to serve as a mild deoxidizer, which precludes having a wild heat in the ladle, passing the steel through a vacuum zone, where oxygen and carbon are removed, and then adding aluminum as a further deoxidizer. The steel thus treated is cast to form a slab or bloom in a continuous-casting machine of any known construction.

This invention relates to steel casting processes and products, and more particularly to processes for vacuum deoxidizing and continuous casting of slabs of sheet and tin plate grades and to steel slabs of novel composition which are thus deoxidized and cast.

Steel slabs for sheet and tin plate applications are generally produced from rimmed and capped steel ingots formed in a conventional ingot mold. Rimmed steel ingots, which account for the greater part of the steel used in making sheet and tin plate, are characterized by a clean, blowhole-free surface of relatively low carbon content, and an interior which has a blowhole structure and a higher carbon content than the surface. As is well known in the art, the obtaining of the desired blowhole structure is essential to producing good quality rimmed steel. Rimmed steel ingots generally contain about 0.05% to about 0.15% by weight of carbon, about 0.2% to about 0.6% by weight of manganese, and less than 0.02%, preferably not over 0.01% by weight of silicon. The liquid steel for such ingots has a relatively high but precise oxygen content which will give the desired rimming action in the mold. Such steel is tapped from a steel making furnace into a tap ladle, with an oxygen content greater than that required in the ingot mold. A metallic deoxidizer is usually added in the tap ladle in order to reduce the oxygen content to the desired level before pouring the steel into the ingot mold. Aluminum is the preferred deoxidizer, and forms alumina, most of which floats to the top of the steel in the ladle to form a scum. The amount of alumina retained in the ingot as inclusions is small and has no significant adverse effect on steel quality. Silicon is avoided as a deoxidizer for rimmed steels, because it forms silicate inclusions which have a detrimental effect on steel quality. Residual silicon in excess of 0.02% generally considered the maximum permissible amount in rimmed steels, results in excessive inclusions because of the relatively high oxygen content of the steel.

Killed steels have been made according to prior art practice when steel free from blowhole has been required. Such steels contain less than about 50 parts per million of oxygen. These steels are usually made using large quantities of aluminum as the deoxidizer, and are cast in conventional ingot molds.

Blowholes can also be avoided by keeping the carbon content of the steel below about 0.02% by weight. At these low carbon levels, carbon monoxide is not formed regardless of the oxygen content of the steel, hence blowholes are not formed. However, steels of such low carbon contents are comparatively weak, and higher carbon contents are frequently desired.

It has long been considered desirable to produce steel by continuous casting, because fewer operations are necessary in the production of continuous cast steel than in the production of steel slabs from conventional ingots. However, no satisfactory steel-making practice which is capable of making steel slabs suitable for sheet and tin plate uses has yet been achieved. The practices used in making rimmed and capped steels in conventional ingot molds are not at all suited to the making of steel by continuous casting. Continuously cast slabs must be free from blowholes. The presence of blowholes in continuously cast slabs is exceedingly detrimental, because blowholes at the surface of the slab impair surface quality, requiring considerable conditioning and frequent scraping of the slab, and internal blowholes substantially reduce the heat conductivity of the slab, making it necessary to operate at low casting speeds. The necessity for eliminating blowholes from continuously cast slabs requires a steel of lower oxygen content than that used in the making of rimmed and capped steel ingots. However, the use of conventional metallic deoxidizers, i.e., aluminum and silicon, in the amounts necessary to reach this low oxygen level, cannot be tolerated since excessive amounts of oxides result. When aluminum added to the tap ladle is the sole deoxidizer, a large quantity of alumina scum is formed, and much of this scum is trapped in the surfaces of the slab as it is formed in the mold, producing a slab of poor surface quality which must be conditioned extensively by sanding. The use of silicon alone as a deoxidizer in continuous cast steel has also proved detrimental. The amount required for deoxidation produces a steel having unacceptably high hardness. Furthermore, the addition of silicon forms silica inclusions, which impair both the surface structure and the internal quality of the slab. The presence of silica inclusions is harmful, especially in hot rolled sheet products.

Vacuum deoxidation of steel in order to reduce its oxygen content prior to continuous casting has also been suggested. However, the oxygen content which can be attained when operating at a commercially feasible rate of speed, is too high to avoid the formation of blowholes whenever the amount of carbon in the steel is above approximately 0.02% by weight. Therefore vacuum deoxidation cannot be used alone to reduce oxygen content to the required level.

Since presently known steel deoxidation procedures cannot give a continuously cast slab of good quality for sheet and tin plate applications, a new procedure is required which will give blowhole-free slabs having low oxygen content and only a small amount of non-metallic inclusions.

An object of this invention is to produce blowhole-free steel slabs suitable for sheet and tin plate applications by continuous casting.

A further object of this invention is to produce a steel slab of novel composition useful for making steel sheet and characterized by low oxygen content and low content of silica and alumina inclusions.

A still further object is to provide a deoxidation practice which results in only small amounts of alumina scum.

These and other objects will be apparent from the specification which follows.

It has been found according to this invention that clean
3,459,537

![Image](image-url)

3,459,537 blowhole-free continuously cast slabs can be formed by vacuum carbon deoxidation followed by deoxidation with one or more metallic deoxidizers, even though neither deoxidation practice alone will produce such slabs.

According to the process of this invention, steel is vacuum-carbon deoxidized to eliminate a substantial portion of its oxygen content, and the degassed steel is then further deoxidized with one or more metallic deoxidizers in order to further reduce the dissolved oxygen content prior to casting the steel. The deoxidized steel is then cast into a water-cooled continuous casting mold, and a partially solidified slab is withdrawn therefrom.

The degased and continuously cast steel slabs of this invention are characterized by low oxygen content, good surface free from alumina scum contamination, and low quantities of silica and alumina inclusions. The total oxygen content of slabs of this invention is less than about 150 parts per million, and the amount of oxygen not combined with silicon, aluminum or manganese is not over about 20 parts per million. The combined quantity of silica and alumina inclusions is not over 150 parts per million.

This invention will now be described with particular reference to the accompanying drawings, in which:

FIG. 2 is a schematic diagram of the apparatus used in the practice of this invention.

In order to obtain steel which is free from blowholes, it is necessary either to reduce the carbon content of the steel to less than about 0.02% prior to solidification, or to reduce the oxygen content to a low level at which blowholes will not form. The exact steel carbon content at which blowholes will not form will vary slightly from 0.02% as it is affected by variables such as steel manganese content. This invention is concerned with processes for reducing the oxygen content of steel to amounts which will give blowhole-free steel. Referring to FIG. 1, the composition range in which blowholes will not form is represented by the region to the left and below Curve A, which shows the maximum permissible concentration of oxygen for any given carbon content in the range of about 0.02% to 0.16% by weight. This maximum oxygen concentration varies from about 10 to 50 parts per million, depending on carbon content. Curve A refers to a stationary ingot mold. As will be explained later, blowholes can be avoided in continuously cast slabs at oxygen concentrations above those given by Curve A, provided casting speeds are maintained above a certain minimum which vary with dissolved oxygen concentration.

A steel melted in any conventional steel-making furnace may be formed into continuously cast slabs of steel and tin plate grade according to this invention. The steel is tapped from a steel-making furnace 10 into a tap ladle 11 (see FIG. 2) at a temperature generally about 3000° F., although the temperature may be somewhat higher or lower.

The steel, as it is tapped, contains a quantity of carbon which yields a product slab containing about 0.02% to 0.15% by weight of carbon after vacuum carbon deoxidation. The amount of carbon is controlled in accordance with the desired use of the product steel. Since the carbon content is reduced by an amount which may range from about 0.01% to 0.05% of the weight of steel, usually about 0.02% to 0.03% the steel as tapped will contain from about 0.04% to about 0.17% by weight of carbon.

The oxygen content of the steel as it is tapped from the furnace 10 may range from a maximum of more than 600 parts per million when the carbon content is 0.04% by weight, down to about 120 parts per million when the carbon content is about 0.17% by weight. The amount of oxygen in steel as tapped from the furnace is given approximately by Curve B, which shows the amount of dissolved oxygen in equilibrium with dissolved carbon at atmospheric pressure and 3000° F.

Small amounts of metals, e.g., up to 1.0% by weight of manganese, not more than 0.1% by weight of silicon, and up to 0.25% by weight of aluminum may also be present in the steel as tapped from furnace 10.

Referring to FIG. 2, after molten steel is tapped from furnace 10 into tap ladle 11, the tap ladle 11 is transported along a path 12 to the top of a continuous casting tower 13 which includes a continuous in-line degassing vessel 14, an open-ended tubular or incased continuous casting mold 15, a plurality of guide rolls 16, and pinch rolls 17.

Additions of metallic deoxidizers and alloying elements may be made in tap ladle 11. From the standpoint of steel cleanliness, it would be preferable to omit deoxidizers altogether in the tap ladle. However, the addition of metallic deoxidizers to the tap ladle is desirable because it minimizes the occurrence of hot tears, i.e., heats having an excessive oxygen concentration in tap ladle 11, and because it makes a greater steel throughput possible by transferring part of the deoxidation load from the degasser 14 to tap ladle 11. Since the use of metallic deoxidizers in tap ladle 11 increases inclusions and scum formation, only limited amounts of deoxidizers are added in tap ladle 11. The quantity of oxygen remaining in the steel as it is tapped from ladle 11 into degasser 14 is substantially greater than that given by Curve C in FIG. 1, which indicates attainable oxygen levels which are attainable by vacuum carbon deoxidation at commercially attractive rates.

Silicon is the preferred deoxidizer for addition to tap ladle 11. Silicon is a mild deoxidizer, and may be added in amounts which will not increase the carbon content above 0.10% by weight of total (free and combined) silicon. It is generally desirable to add enough silicon to raise the silicon content of the steel to at least 0.02% by weight in order to assure proper deoxidation. Higher silicon contents are avoided because of the high hardness and poor drawing qualities of the resulting steel. Up to about 4 pounds per ton of silicon can be added in the tap ladle without exceeding 0.10% of silicon in the product. The apparent discrepancy between the amount of silicon added and the resulting silicon content of the steel is explained by the fact that the silicon is not fully extracted from the silicon containing slag in ladle 11 and 12, as it is not accounted for in subsequent analyses. Silicon can be added to the steel in tap ladle 11 in the form of an alloy such as ferrosilicon or silicon-manganese.

Addition of silicon in tap ladle 11 reduces the oxygen content to a level given approximately by Curve D in FIG. 1. Curve D shows the equilibrium dissolved oxygen content of steel at various concentrations of dissolved (elemental) silicon in the range of about 0.01% to about 0.16% by weight at 2910° F. in steel containing 0.4% by weight of manganese. This temperature and manganese content represent typical conditions in the tap ladle. The amount of dissolved oxygen decreases as the amount of silicon added is increased. At equilibrium, the oxygen content of the steel is less than it was at the time of tap but substantially greater than the oxygen content after degassing, and a substantial amount of elemental silicon remains in solution. Since silicon becomes a progressively more powerful deoxidizing agent as the steel temperature drops, this dissolved silicon is available for further deoxidation of the steel after it has been degassed and as it is being cooled. More about this will be said later.

Aluminum is a powerful deoxidizer which may be added in small amounts up to about 0.75 pound per ton of steel in tap ladle 11. Larger amounts are because an excessive quantity of alumina is formed. Ladle additions of aluminum in any amounts are undesirable from the standpoint of steel cleanliness. Although the
alumina formed tends to float to the top of the ladle, some of the alumina is carried through the process with the steel and ultimately is carried into the mold where it mars the casting surface. Furthermore, ladle aluminum is inefficient and unpredictable as a deoxidizer. Much of it is consumed, by air oxidation for example, without reducing the dissolved oxygen content of the steel.

The most desirable practice from the standpoint of steel cleanliness is not to add any deoxidizers in ladle 11. This practice minimizes the quantity of silica and alumina inclusions. However, some ladle deoxidizer is desirable in order to avoid "wild" heats, i.e., heats containing too much dissolved oxygen in the steel.

Manganese generally added to ladle 11 in amounts which will give a manganese content of 0.1% to 1.0% by weight in the product slab. Manganese is added in the form of an alloy such as ferromanganese or siliconmanganese. A portion of the manganese added is oxidized to manganese oxide, MnO.

Steel is continuously teemed from tap ladle 11 into degassing vessel 14. This is done after the addition of deoxidizers and alloying elements in ladle 11 when such additions are made. The steel, as it is teemed from ladle 11 into degassing vessel 14, contains about 0.04% to about 0.17% by weight of carbon, about 0.1% to about 1.0% by weight of manganese, less than about 0.005% by weight of aluminum, not more than about 0.10% by weight of silicon, and about 120 to about 600 parts per million of oxygen. Whether ladle deoxidizers are used or not, the dissolved oxygen content of the steel as it is teemed into degasser 14 must be substantially in excess of the amount of oxygen given by Curve C in FIG. 1, so that the degasser will be used effectively and the quantity of inclusions formed by the use of metallic deoxidizers held to a minimum.

The temperature drop of steel in the tap ladle 11 should be as small as possible. This temperature drop is about 50°F on average, although this amount can vary widely. In a typical operation, steel is tapped from furnace 10 at about 3000°F or slightly higher and is teemed into degasser 14 at about 2900°F.

Degasser 14 is operated at a maximum pressure of about 50 mm. of mercury absolute and preferably about 3 mm. of mercury absolute. The high vacuum prevailing in degasser 14 removes substantial quantities of oxygen from the steel, together with some carbon and yields a degassed molten steel whose oxygen content is approximately equal to that given by Curve C in FIG. 1. This curve can be represented by the equation:

$$p.p.m.\text{ of oxygen} = 8.7/(\text{percent } C)^{0.75}$$

This equation is typical of an oxygen content which is actually attainable in an in-line degasser operating at a reasonable rate. The equilibrium concentration of oxygen under high vacuum at steel degassing temperature lies below Curve C, but this equilibrium concentration is of no practical significance because equilibrium can be reached only at very slow degassing rates which would not be practical in commercial operation.

A preferred degasser for use in the present process is a continuous in-line degasser having an upper inlet opening 21 for undegassed metal, a bottom discharge opening 22 controlled by a sliding gate valve 23 actuated by a hydraulic cylinder 24, an opening 25 in the side wall of the degasser 14 to permit the introduction of metallic deoxidizers into the pool 26 of degassed steel which collects in degasser 14, and deoxidizer feeding means 27. A preferred form of deoxidizer feeding means 27 includes a spool 28 for feeding aluminum in wire form, a tube 29 extending outwardly from opening 25 and in fluid-tight engagement therewith, and a seal 30 at the outer end of the tube 29 which permits feeding of aluminum wire to degasser 14 while maintaining a vacuum tight seal. The degasser has conduits 31 and 32, communicating with the opposite sides of baffle 33 and connected to a source of high vacuum. The continuous in-line degasser 14 shown in FIG. 2 is preferred because of the low steel temperature drop which takes place in this type of degasser.

Generally the temperature drop in degasser 14 is only about 10°F. Other types of degassers such as the known ladle type of batch degasser, may be used instead. Such degassers frequently can achieve comparable degassing results, but generally cause a much greater steel temperature loss, e.g., 100°F or more.

Degassing in vessel 14 results in a reduction of the carbon content of the steel by about 0.01% to about 0.05% by weight, usually about 0.02% to about 0.03% by weight, based on the total weight of steel, and a corresponding oxygen reduction of more than 30%, even for each 0.01% by weight of reduction in the carbon content. The reduction in oxygen content is due to a reaction between oxygen and carbon to form carbon monoxide. Thus when the carbon content is reduced by 0.02%, the oxygen content drops by about 260 parts per million. The steel, after degassing, contains from about 0.02 to about 0.15% by weight of carbon. The dissolved oxygen content of the degassed steel is given by Curve C in FIG. 1.

The quantity of oxygen remaining dissolved in the steel after it has been degassed is still so high as to form blowholes in the cast slab, so that the metal must be further deoxidized before it is solidified. An essential feature of this invention is the deoxidation of the degassed molten steel with one or more metallic deoxidizers, in order to reduce the dissolved oxygen content.

The preferred deoxidizers for degassed steel are aluminum and silicon, although other metallic deoxidizers such as boron are also usable.

Aluminum is the preferred deoxidizer for degassed metal. Since aluminum is the most powerful deoxidizer which is compatible with steel, the use of aluminum as the deoxidizer produces steel of the lowest possible dissolved oxygen content. Furthermore, the use of aluminum instead of silicon results in steel having a very desirable hardness and a minimum of silica inclusions.

It may be added to the degassed steel under vacuum in degasser 14 as aforesaid, or may be added at the top of mold 15. In either case, it is in a preferred form of aluminum oxide for deoxidating degassed metal. About all of the aluminum added in tap ladle 11 is oxidized there, additional aluminum must be supplied to the degassed metal when deoxidation of degassed metal with aluminum is desired. Aluminum is utilized much more efficiently in degasser 14 or mold 15 than in ladle 11. While much of the aluminum added in degasser 14 or mold 15 is used to deoxidize steel, and only a small quantity is oxidized by extraneous oxygen, such as that picked up from the atmosphere in teeming from degasser 14 to mold 15.

Aluminum added in degasser 14 will reduce the oxygen content of the steel to a very low level, indicated approximately by Curve E in FIG. 1, which shows oxygen concentration at equilibrium as a function of the amount of dissolved (i.e., acid-soluble) aluminum in the steel. This effectively kills the steel provided enough aluminum is used, preventing blowhole formation in the cast slab.

Silicon may also be used to deoxidize degassed metal. The silicon for this purpose may be residual dissolved silicon which was added to the steel in tap ladle, or may be silicon added to the degassed metal, either in degasser 14 or at the top of mold 15. In either case, conventional silicon alloys such as ferrosilicon and silicomanganese are used. Silicon added to degassed metal is somewhat more efficiently utilized than silicon added in tap ladle 11.

Silicon becomes a more powerful deoxidizing agent as temperature decreases, as already indicated. As the steel is cooled and gradually solidified in and below mold 15, further reaction between silicon and oxygen takes place, reducing the oxygen content below that attained in...
degasser 14 (shown by Curve C) to an acceptable level at which blowholes will not form. The total amount of silicon added in ladle 11 and degasser 14 must not give a silicon content greater than 0.10% by weight in the cast slab. The maximum tolerable silicon content decreases with increasing carbon content in accordance with the equation:

\[ \text{percent Si} + 0.5\% C = 0.11 \]

Thus steel containing 0.02% carbon may contain the maximum 0.1% of silicon. Steel containing 0.06% carbon should not contain more than 0.08% by weight of silicon, and steel containing 0.15% by weight of carbon should contain no more than 0.03% by weight of silicon.

The dissolved oxygen content attained with silicon is higher than that attained with aluminum, but is nevertheless low enough to prevent blowhole formation, provided the casting speeds hereinafter described are observed. While the final oxygen content is frequently in the killed region below Curve A (FIG. 1) when aluminum is used, the final oxygen content is more likely to lie slightly above Curve A when silicon alone is used, so that minimum casting speeds must be maintained in order to prevent blowhole formation.

Degassed steel is continuously teemed from degassing vessel 10 into mold 15. The outflow rate from degasser 14 equals the inflow rate in steady state operation. Mold 15 is a conventional water-cooled, open-ended continuous casting mold. A solidified shell of metal is formed in mold 15, and this solidified shell becomes progressively thicker as the cast slab descends below mold 15 until the slab is completely solidified.

When silicon alone is the metallic deoxidizer for degassed metal, the gradual cooling and solidification of the slab causes further reaction between silicon previously added and dissolved oxygen in the steel takes place, reducing the oxygen content to a level at which blowholes will not form, provided the casting speed is not allowed to fall below a critical minimum which depends on the dissolved oxygen content of the steel.

The limitation on the quantities of aluminum and silicon which may be used as deoxidizers without exceeding the maximum of 0.1% by weight of silicon and 0.015% by weight of aluminum may result in low having sufficiently high dissolved oxygen content that freedom from blowholes cannot be guaranteed. It has been found, however, that such heats will be free from blowholes provided a certain minimum casting speed, which depends on the dissolved oxygen content of the steel, is maintained. For this reason high casting speeds are preferred over low casting speeds. For example, in a heat containing about 20 parts per million of oxygen which is not chemically combined with aluminum, silicon, or manganese, freedom from blowholes is assured if the casting speed is at least 50 inches per minute. Where the amount of oxygen not chemically combined is less than 20 parts per million, the minimum casting speed which must be maintained is proportionately lower.

The cast slab, when solidified, contains about 0.02% to about 0.15% by weight of carbon, not more than about 0.10% by weight of silicon, about 0.1% to about 1.0% by weight of manganese, and not more than about 0.015% by weight of aluminum. The total oxygen content is less than about 150 parts per million, and preferably less than 100 parts per million. The amount of oxygen not chemically combined with aluminum, silicon, and manganese is present in amount not over about 20 and preferably less than 10 parts per million. The combined amount of silica and alumina inclusions is not over 150 parts per million. The amount of silica inclusions will be less than 100 parts per million when the preferred deoxidation practice using aluminum in the degasser is used.

The steel of this invention is ideally suited for formation into sheet and tin plate, which may be accomplished by known methods. The mechanical properties, e.g., tensile strength, hardness and elongation, are excellent for shear and tin plate. The steel of this invention has excellent drawing qualities.

This invention will now be described further with reference to the following examples.

Example 1

Molten steel was tapped from a basic oxygen process furnace 10 into a tap ladle 11. The carbon content at tap was 0.038% by weight, the residual manganese content was 0.27%, and the tap temperature was 3050°F. Alloying additions of 12.1 pounds per ton of medium carbon ferromanganese and 1.4 pounds per ton of aluminum were made in the tap ladle. This corresponds to 0.50% by weight of manganese, 0.01% by weight of carbon, 0.07% by weight of aluminum and 0.01% by weight of silicon. The carbon content of the steel after ladle additions was 0.043% by weight and the oxygen content was 217 parts per million.

The heat was degassed in degassing vessel 14. The degassing vessel was maintained at an absolute pressure of about 3 mm. of mercury. Aluminum wire was continuously fed into the pool of the degassed metal in degasser 14 at an initial rate of 0.25 pound per ton, which was reduced to 0.12 pound per ton during the course of degassing.

The degassed steel was continuously poured from degasser 14 into a continuous cast mold 15. This mold was an open ended tubular water cooled mold. The molten metal began to solidify inwardly from the mold walls. The partially solidified cast slab was withdrawn from mold 15 at a speed of about 80 inches per minute. As the slab descended below the mold it was further cooled with water and gradually solidified. The slabs were cut into lengths, and were examined for surface quality and internal structure. The surfaces were of good quality requiring little or no scarfing. The internal structure was free from blowholes.

Analysis of the cast slab showed 0.030% by weight of carbon, 0.50% by weight of manganese, 0.022% by weight of silicon, 0.005% by weight of aluminum and 118 parts per million of oxygen. These elemental analysis include both free and combined forms of the elements.

The oxygen content was determined by vacuum fusion analysis.

Analysis of the inclusion by the ester halogen extraction technique showed 67 parts per million of silica, 57 parts per million of alumina, and 152 parts per million of manganese-oxide. The total combined oxygen accounted for by these three oxides is 98 parts per million. The product slab had a yield strength of 23,600 pounds per square inch, a tensile strength of 46,000 pounds per square inch, an elongation (2 inches) 39.6%, and a Rockwell B hardness of 35.8%.

Example 2

Molten steel was tapped from a basic oxygen furnace 10 into tap ladle 11. The carbon content of the bath at tap was 0.043 percent; the residual manganese was 0.27 percent, and the tap temperature was 3020°F.

The tap ladle additions were 9.1 pounds per ton of high carbon ferromanganese, 2.6 pounds per ton of 50% ferrosilicon, and 1.4 pounds per ton of aluminum. This corresponds to 0.36% by weight of manganese, 0.03% by weight of carbon, 0.07% by weight of aluminum, and 0.07% by weight of silicon. The ladle additions increased the carbon content of the steel to 0.071 percent.

The oxygen content of the steel after ladle additions and prior to degassing was 217 parts per million.

The heat was degassed in-in-line degasser at 3 mm. of mercury, during which operation the carbon content of the steel was decreased to 0.057 percent. No aluminum was fed into the vacuum system during the degassing
operation. The steel was cast as described in Example 1, at 90 inches per minute.

The steel was cast as described in Example 1, at 90 inches per minute. The product analysis as weight percent was: C, 0.055; Mn, 0.41; P, 0.01; S, 0.01; Si, 0.05; and oxygen, 0.0065.

The product analysis as weight percent was: C, 0.055; Mn, 0.41; P, 0.01; S, 0.01; Si, 0.05; and oxygen, 0.0065.

The inclusions in the steel as determined by the ester halogen extraction technique as parts per million was:

Example 3

The procedure of Example 2 was followed except that the ladle additions were as follows: 8.2 pounds per ton of high carbon ferromanganese, 5.4 pounds per ton of 50% ferrosilicon, and 0.76 pound per ton of aluminum. This corresponds to 0.32% by weight of manganese, 0.03% by weight of carbon, 0.07% by weight of aluminum and 0.13% by weight of silicon. The tap carbon content was 0.035%, and the carbon content after ladle additions was 0.065%.

The product analysis as weight percent was: C, 0.035; Mn, 0.44; P, 0.01; S, 0.01; Si, 0.08; and oxygen, 0.0087. The inclusions in the steel as determined by the ester halogen extraction technique was:

SiO₂, 120; Al₂O₃, 27; and MnO, 92. The amount of oxygen chemically combined in these oxides was 99 parts per million.

While this invention has been described with respect to specific embodiments thereof, it is understood that there are by way of illustration and not limitation.

What is claimed is:

1. A method of producing steel free of blowholes in a continuous-casting process comprising:

(a) introducing to a ladle molten steel which has a carbon content of at least 0.04% by weight and a dissolved oxygen content substantially exceeding that given by the equation

\[ p.p.m. \text{ of } O_2 = 8.7 / (\text{percent } C)^{0.75} \]

(b) introducing silicon to the steel in the ladle in an amount to produce a silicon content in the steel of about 0.02 to 0.10% by weight, thereby lowering the dissolved oxygen content of the steel to a value closer to but above that given by the foregoing equation;

(c) transferring the steel from the ladle to a vacuum degassing zone where carbon and oxygen contained

in the steel react to lower the carbon content by about 0.01% to 0.05% and the oxygen content approximately to the value given by the foregoing equation;

(d) introducing aluminum to the degassed steel, thereby further lowering the dissolved oxygen content thereof and minimizing silica inclusions therein; and

(e) continuously casting a slab of the steel, which slab has a carbon content of about 0.02% to 0.15% by weight, a maximum oxygen content of about 150 p.p.m., a maximum silicon content of about 0.1% by weight, and a maximum aluminum content of about 0.015% by weight.

2. A method as defined in claim 1 in which the oxygen content of the molten steel after introduction of silicon but before the steel enters the vacuum degassing zone is given approximately by Curve D of FIGURE 1.

3. A method as defined in claim 1 in which aluminum is introduced to the steel while the steel remains in said degassing zone.

4. A method as defined in claim 1 in which aluminum is introduced to the steel after the steel discharges from said degassing zone.

5. A method as defined in claim 1 in which the slab is cast at a speed of at least 50 inches per minute.

References Cited

UNITED STATES PATENTS

3,125,440 3/1964 Hornak et al. 75—49
3,145,096 8/1964 Finkl 75—49
3,183,078 5/1965 Ohtake et al. 75—49
3,208,844 9/1965 Kato et al. 75—49
3,226,224 12/1965 Sickbert 75—49
3,230,074 1/1966 Roy et al. 75—49
3,266,636 2/1966 Finkl 75—49
3,239,390 3/1966 Matukura et al. 148—12.1
3,337,330 8/1967 Finkl 75—49

OTHER REFERENCES


CHARLES N. LOVELL, Primary Examiner

U.S. Cl. X.R.

75—58, 129; 164—56, 82