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3,748,122

**METHOD FOR DYNAMICALLY CONTROLLING
DECARBURIZATION OF STEEL**

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3 Claims

ABSTRACT OF THE DISCLOSURE

Described herein is a method of dynamically controlling decarburization of steel by measuring the rate of carbon removal from the steel, measuring the rate of oxidizer input, continuously maintaining a balance between the aforementioned rates by adjusting the carbon-oxygen reaction rate and/or adjusting the input of oxidizing material to the steel.

This application is a division of application Ser. No. 771,752, filed Oct. 30, 1968, now Pat. No. 3,594,155, issued July 20, 1971.

This invention relates to decarburizing steel. More particularly, the invention relates to an improvement in the method of decarburizing molten steel wherein oxidizing material is introduced to the steel to react with carbon contained therein. Still more particularly the improvement in accordance with the invention comprises a dynamic method of controlling decarburization of molten steel by measuring the rates of carbon removal from the molten steel, oxidizer input rate, continuously maintaining a balance between the two rates by adjusting the carbon-oxygen reaction rate and/or oxidizer input rate in response to the measured rates. The term "balance" as used herein means adjusting the relationship between the rates of carbon removal from the steel and oxidizer input to achieve any desired result. For example, avoidance of oxidation of expensive alloying elements is achieved by maintaining a balance such that the rate of oxidizer input is never greater than the rate of carbon removal.

Decarburizing is an essential part of present day steel making practices and more and more commonly is performed by blowing pure oxygen into the melt contained in a vessel or furnace, e.g. electric furnace, open hearth, basic oxygen furnace (BOF), etc. This so called "oxygen steel making" now is practiced in both the manufacture of plain carbon steel and alloy steel. The oxygen efficiency for decarburization processes of the type described can be defined as:

$$\text{Percent oxygen efficiency} = \frac{\text{oxygen to the decarburization reaction}}{\text{net oxygen to the system}} \times 100$$

This efficiency figure can be used to check how effectively the oxygen is used to remove carbon. Although the prime purpose of oxygen is the removal of carbon, it will also oxidize silicon, phosphorus and, if not properly controlled, other metallic values. It is apparent that to make best use of oxygen, control of the factors affecting oxygen efficiency is necessary.

The present invention, which is useful in both vacuum and atmospheric pressure decarburization and for alloy steel as well as plain carbon steel, involves dynamically balancing the rate of oxygen input and the rate of carbon removal and adjustment of the carbon removal rate and/or oxygen input rate to achieve any particular maximum oxygen efficiency or any other desired result. Thus, for example, by practicing the invention it is possible to adjust the oxygen input so that the normal preferential oxidation of carbon can be accomplished without loss

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of more valuable metal values such as chromium and other alloying elements. This is achieved by assuring that the total oxygen available during decarburization does not exceed that needed for carbon removal.

The carbon removal rate can be determined by any of several ways. Thus for example, the composition of the bath can be continuously sampled and analyzed for carbon to determine the quantity of carbon removed per unit of time. Another, and presently preferred method, is to monitor the exhaust gases from the reaction vessel and measure the total flow and the amounts of carbon monoxide and carbon dioxide in the off-gas stream such as by the techniques described below. Analyses of off-gas composition and measurement of flow can be used to determine the rate of carbon removal almost instantaneously. This rate of carbon removal, which can be expressed conveniently as pounds per minute, is equal to the volume of carbon monoxide and carbon dioxide leaving the furnace at any given moment multiplied by a conversion factor. Set forth in an equation, this relationship is expressed as follows:

$$\begin{aligned} \text{Lbs. of carbon removed/min.} &= (\text{volume percent CO} \\ &+ \text{volume percent CO}_2 \text{ in the off-gas}) - X \text{ flow} \\ &\text{rate of off-gas (standard cubic ft./min.)} \times \frac{12}{359} \end{aligned}$$

(12=atomic weight of carbon, 359=conversion factor based on fact 359 cubic feet of a gas contains a mole of gas).

Similarly, the volume of equivalent oxygen that has reacted with this carbon at any time during the process may be obtained by the following equation which gives the rate at which oxygen is consumed by the carbon. For practical purposes this consumption rate is expressed as cubic feet per minute to correspond to the flow rate of the off-gases.

$$\text{Rate at which oxygen is consumed by the carbon (standard cubic feet/min.)} = \frac{1}{2} [\text{vol. percent CO in off-gas} + \text{vol. percent CO}_2 \text{ in off-gas}] \times \text{flow rate of off-gas (standard cubic feet/min.)}$$

Whether the oxygen supplied to the vessel for decarburization is being consumed by the carbon in the melt or whether metallic elements are being oxidized can be determined by noting whether the rate of oxygen consumed by the carbon is greater, equal to or less than the rate of oxygen input. Adjustment of the oxygen input can be made in response to the measured rates of carbon removal and oxygen consumption. By continuously adjusting the variables responsible for the carbon-oxygen reaction and/or the flow rate of oxygen into the reaction vessel the decarburization reaction may be continuously, i.e. dynamically balanced.

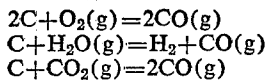
The oxygen input rate and/or the carbon removal rate can be varied in accordance with the measured rates of carbon removal and oxygen consumption by varying the oxygen efficiency which amounts to altering the rate of the carbon-oxygen reaction. This can be varied by several means, such as:

- (1) Changing the oxygen input rate, e.g., by including a diluent gas or increasing the proportion of diluent gas mixed with oxygen introduced to the reaction vessel;
- (2) Changing the pressure in the vessel;
- (3) Changing the temperature of reaction; and
- (4) Changing the reaction surface area, i.e. agitating or increasing the mixing of oxygen and steel.

Change in the oxygen input rate may be accomplished by simply reducing the flow rate of oxygen when pure oxygen is used. In this way, the mixing caused by the input of the gas is reduced and the oxygen consumption rate is also reduced. However, if the total gas flow rate is maintained and a non-reactive gas, e.g. a diluent, is sub-

stituted for oxygen, the rate of oxygen reaction with carbon is not lowered. Thus, the oxygen input rate can be varied by including a diluent gas with oxygen, but maintaining the same total gas flow rate, without reducing the rate of oxygen reaction with carbon. Diluent gases which may be used other than inert gases are, for example, hydrogen and carbon monoxide as well as steam or carbon dioxide. Carbon dioxide and carbon monoxide do not displace the equilibrium of the carbon-oxygen reaction in any way.

The amount of oxidizing material required for carbon removal in an input gas stream can be calculated using the gaseous composition, the mass flow rate and the stoichiometry of the reactions within the steel melt. The reaction of these oxidizing gases with carbon in the melt can be written as:



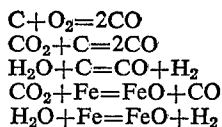
It is evident from the above that the same volume of carbon dioxide and steam can combine with only half as much carbon as pure oxygen. Thus the total oxidizing material, i.e. gaseous input, in terms of oxygen equivalent, can be calculated by the following equation:

Volumetric flow rate of oxidizer (expressed as volumes of O_2 per unit time) = volumetric flow rate of oxygen in input gas + $\frac{1}{2}$ (sum of the volumetric flow rates of carbon dioxide and steam in input gas)

The rate of carbon removal must be corrected for the carbon input to the system. This correction can be obtained by measuring the volumetric rate at which carbon is fed into the system as carbon monoxide or carbon dioxide. The carbon input can be expressed in terms of oxygen equivalent as follows:

Carbon input (volumetric rate in equivalent oxygen units) = $\frac{1}{2}$ (sum of volumetric flow rate of carbon monoxide and carbon dioxide in input gas)

To complete the dynamic balance, the products of reaction, specifically the amount of oxidizing material combined with carbon in the melt, must be estimated. One technique of the many that may be used, is to determine the composition of the exhaust gases and the exhaust gas flow rate. It may be assumed that the exhaust gases contain all of the inert or diluent gases and the gaseous products of reaction with the melt. In addition, the exhaust gases will also include the unreacted portions of the input gas and other gases entering the system. The reaction products can be viewed as:



(Note: Instead of iron, any other metallic element can combine with steam or carbon dioxide to form H_2 or CO .)

The amount of oxygen needed for decarburization can be calculated from the composition and flow rate of the exhaust gas. The flow rate from the exhaust gas can either be estimated by means of a calibrated orifice plate or can be calculated using a tracer gas technique. In the latter, a tracer gas at a known flow rate can be mixed completely with the exhaust gas and the flow rate of the exhaust gas can be calculated. Whenever an inert gas such as argon is used in gas mixture with oxygen, the inert gas, e.g. argon, can be used as the tracer gas and the volumetric flow rate obtained as follows:

Volumetric flow rate of exhaust gas = $\frac{100 \times \text{volumetric flow rate of input argon}}{\text{Volume percent argon in output stream}}$

The presence of air leaks will affect the determination of volume flow rate when argon is used since air contains on order of 0.94% argon by volume. A correction can be made where argon concentrations added by the air is discounted.

Corrected estimate of volumetric flow rate of exhaust gas = $\frac{100 \times \text{volumetric flow rate of input oxygen}}{\text{volume percent argon in exhaust gas}} - \left[\frac{0.94}{78.08} \times (\text{volume percent } N_2 \text{ in exhaust gas}) \right]$

When mixtures of steam and oxygen are used, the hydrogen portion of the steam can be used as the tracer and the volumetric flow rate of the exhaust gas can be determined as follows:

Volumetric flow rate of exhaust gas = $\frac{\text{Volumetric flow rate of steam} \times 100}{\text{Sum of percentages of hydrogen and steam in exhaust gases}}$

After determining the flow rate of the exhaust gases the carbon removal rate can be measured. This can be done on an oxygen equivalent basis by the following equation:

Carbon removal rate (in volumetric flow rate in equivalent O_2 units) = $\frac{1}{2} \times \text{volumetric flow rate of exhaust gases} \times (\text{sum of volume percent of } CO \text{ and } CO_2) - \text{carbon input}$

To up-date and correct the determination of oxygen required for carbon removal, it may be necessary to consider small amounts of unreacted oxygen or steam that can leave the system along with other products of reactions which have not gone to completion. To provide such correction, the following relationship may be used:

Corrected rate of oxygen required for the carbon removal = carbon removal rate + volumetric exhaust gas flow rate $\times (\frac{1}{2} \text{ volume percent } H_2O + \frac{1}{2} \text{ volume percent } CO_2 + \text{volume percent } O_2 \text{ in exhaust gases})$

The dynamic balance between the actual total oxygen input rate and the corrected rate of oxygen required for carbon removal can be performed by comparing the input and output rates. The input rate can be determined according to the following expression:

Total oxygen input rate (volumetric flow units) = volumetric flow of oxidizer input + $\left[\frac{20.95}{78.08} \times \frac{\text{volumetric percent } N_2 \text{ in exhaust gas}}{100.0} \right]$

As can be seen, the oxygen input rate should account for both the deliberate input oxygen as well as accidental and incidental sources of oxygen such as air or water leaks. Only the two variables, the total oxidizer input rate and the corrected rate of oxygen required for carbon removal are determined. These values can be compared to determine whether the desired balance is maintained.

In decarburizing stainless steel, elements such as silicon and aluminum must, if present, be oxidized before the carbon level can be reduced to low values. In such cases, the rate at which silicon, aluminum, etc., are being oxidized can be measured and included in determining the oxygen input so that sufficient oxygen is provided to accomplish decarburization at the desired rate as well as oxidation of the elements, e.g. silicon, aluminum, also intended to be removed. In such a process the silicon loss rate can be estimated by noting the difference between the rate of input of the oxidizing material and the corrected oxygen rate required for carbon removal. To determine whether metallic oxidation is occurring, the total input rate of oxidizing material may be compared with the estimated oxygen required for carbon removal. If the oxygen input rate is greater than that required for the carbon removal, it can be concluded that metallic oxidation is occurring. To restore the dynamic balance and

avoid metallic oxidation, one or a combination of the following practices may be used.

(1) Lower the content of oxidizing material in the input stream while maintaining its overall flow by increasing the volume of the diluent (the diluent could be one or more of the inert gases such as argon, steam, carbon monoxide or carbon dioxide),

(2) Lower the gas flow rate in systems in which the pressure need not be maintained (this technique will not normally be effective if the system pressure is maintained since the carbon removal rate will also be lowered. The rate of carbon removal could remain the same even with lowered flow rate of input gases since the system pressure could become lower and result in an increase in the driving force for the carbon removal reaction),

(3) Increase the carbon removal rate by increasing the system temperature.

Restoration of balance in decarburization of plain carbon steels can also be accomplished as described above. The essential difference between decarburizing alloy steels and decarburizing low carbon steels is that the iron oxide buildup in the slag in plain carbon steel is desirable for phosphorus removal. The efficiency of carbon removal may be desirably low at the start and then improved as the carbon content is lowered. It is only near the end of the process that elimination of iron loss would be particularly desirable. The efficiency of carbon removal can be controlled by varying lance height or by controlling the rate of additions of lime, ore, etc. Near the end of decarburization the use of carbon monoxide and oxygen or even carbon dioxide and oxygen may be preferred.

Another technique for determining the occurrence of metallic oxidation is by the ratio of inert gases to carbon-containing gases in the exhaust stream. For example, where mixtures of argon and oxygen are used for decarburization, it may be assumed that all of the input oxygen will react with the carbon and the expected ratio of argon to carbon-bearing gases will be as follows:

Expected Ar/(CO+CO₂) ratio

$$= \frac{\text{Percent Ar in input gas}}{2(100 - \text{percent Ar in input gas})}$$

Actual ratio

$$= \frac{\text{Percent Ar in exhaust stream}}{\text{Percent CO} + 2 \times \text{percent CO}_2 \text{ in exhaust stream}}$$

If the expected ratio is greater than the actual ratio, metallic oxidation will be occurring. Corrections for air leaks may also be made to the ratio and if carbon dioxide or carbon monoxide is used in the input stream, adjustments for these components may also be included in the ratio. A similar program can be established for mixtures of steam and oxygen or hydrogen and steam.

Several recent patents discuss the use of a mixture of inert gas and oxygen, especially with reference to stainless steel melting. Among these are U.S. Pat. 3,003,865 which describes the use of inert gas and oxygen for decarburizing stainless steel and Pat. Nos. 3,046,107 and 3,252,770, which describe how argon or other inert gases can be used to exercise some degree of control of the decarburizing process. These patents describe certain theoretical relations, based on thermodynamic equilibria, which are applicable to controlled decarburization of stainless and alloy steels using oxygen and inert gas mixtures. Thus in U.S. Pat. 3,046,107 the maximum oxygen content of a mixture that can be employed for decarburization, with negligible chromium loss, is given by:

Percent oxygen =

$$\left(\frac{13,000}{\left[\frac{\text{Percent Cr}}{\text{Percent C}} \text{ antilog} \left(\frac{13,800}{T} - 8.46 \right) \right] - 1} \right)^{1/2}$$

where Cr and C are the melt chromium and carbon concentrations respectively and T is the melt temperature in

degrees Kelvin. A refinement of the above relationship is given in U.S. Pat. 3,252,770:

$$\text{Percent carbon} = \left[\frac{1}{K_t} (\text{percent Cr})^3 \right]^{1/4} P$$

where K_t is the thermodynamic equilibrium constant derived from the activities of carbon and chromium at the melt temperature, and P is the pressure surrounding the melt.

By applying the above relationships, a theoretical gas supply schedule and decarburization scheme can be derived, involving stepwise, or where possible, continuous reduction of the proportion of oxygen in the injected gas stream as the carbon content of the bath is lowered. An illustration of the application of this technique is the following example of a 15 ton heat processed using the aforementioned relationships. The chemical composition of the melt before decarburization was as follows:

C=0.95%; Mn=0.93%; S=0.012%; Si=0.82%;
Cr=18.42%; Ni=12.17%

An oxygen (68.1% by volume) and argon mixture was injected via subsurface means into the melt for forty (40) minutes, and at the end of this step, the carbon and chromium contents were 0.179% and 17.32% respectively. Subsequently, a 38.5% oxygen-argon mixture was injected for an additional seventeen (17) minutes, at the end of which period, the carbon and chromium levels had decreased to 0.045% and 16.65% respectively. During the process, the melt temperature rose from an initial value of 2820° F. to 3140° F., and 1.77% chromium was lost by oxidation.

It should be observed that according to the provisions of the equations presented previously, the carbon content in equilibrium with the initial chromium in the bath (assuming an average melt temperature of 3000° F.) when a 68.1% oxygen-argon mixture is employed is 0.259%. During decarburization from the initial level of 0.95% to this equilibrium value, carbon was preferentially oxidized. But since gas injection with the 68.1% oxygen mixture proceeded beyond this point, both carbon and chromium were oxidized simultaneously as soon as carbon dropped below 0.259%, and hence the observed chromium loss (to 17.32%). Since, according to the practice described in U.S. Pat. 3,046,107, for a 38.5% oxygen-inert gas mixture, and for a 17.32% chromium content, the equilibrium carbon at 3000° F. is 0.105%, preferential oxidation of carbon was resumed during the second step. However, when decarburization proceeded beyond 0.105% carbon, chromium oxidation again set in and by the end of the process, this element had been reduced to 16.65%. Thus, practicing the embodiments of the previously cited patents does not guarantee "negligible" chromium loss. This is in part due to the inability to recognize the onset of chromium oxidation and to adjust the gas blow accordingly.

The embodiments of the present invention, based on the maintenance of a dynamic balance between the input oxygen and the off-gases from the decarburization process, provide techniques for the accomplishment of decarburization without chromium loss. The application of the invention requires close regulation of, among others, the following parameters:

- Input and entrained gas composition
- Ambient pressure around the melt
- Melt temperature
- Gas-metal contact area

In addition, means should be available for measurement and alteration of each of the above quantities. Several means for achieving these objectives are discussed hereinafter with accompanying examples. In all cases, means for injecting and measuring the rate of flow of the decarburizing gas(es) into the reactor vessel are provided. Suitable gas injection devices are tuyeres, surface lances, submerged lances, etc. Input gas flow rates can be de-

terminated by such means as flow-meters, orifice plates, etc. The composition of the input gases can be generally obtained with gas-analyzing devices such as a mass spectrometer. Similarly, techniques are available for the determination of off-gas compositions. One such technique, which generates a continuous analysis, is the subject of several French patents [Nos. 1,309,212 (Oct. 8, 1962); 1,325,024 (Mar. 18, 1963)]. The method has been published in the *Journal of Metals*, June 1964, p. 508, and is generally familiar to steel making artisans. It involves continuous determination of the carbon monoxide and carbon dioxide contents of the effluent gases from the refining vessel. Such determinations then serve as an indicator of the carbon content and decarburization rate of the melt. The input and off-gas analyses, used as the input for a properly calibrated computer device, yield an instantaneous indication of the processes occurring in the melt. Sampling of the off-gases is difficult since atmospheric air entrained at the mouth of the reactor vessel results in immediate combustion of the off-gases. However, satisfactory samples can be obtained by taking precautionary measures, such as that described by M. Allard et al. in the *Journal of Metals*, June 1961, p. 421. By controlling the pressure between the exhaust hood and the mouth of the reactor vessel, a stationary combustion zone is created for the off-gases, and since the pressure condition prevents an air draft into the area of the vessel mouth virtually all the evolved gases can escape in their pure form into the hood where they can be sampled and analyzed.

In the preferred embodiment, the process of the present invention employs continuous input- and off-gas analysis for the purpose of indicating the efficiency of oxygen consumption by melt carbon. The carbon-oxygen reaction occurs in preference to metallic oxidation if the bath carbon is equal to or above the equilibrium level for the system in question, and if the carbon available for oxidation is at least stoichiometrically balanced by the injected oxidizers. With the aid of a continuous gas analyzer such as described above, the oxygen equivalent of the effluent gases (where oxygen equivalent is given by the sum of unreacted oxygen and the oxygen contents of evolved CO and CO₂) is compared with the injected and entrained gaseous oxygen. A lower value in the effluent stream (and therefore an efficiency of less than 100%) implies that a proportion of the supplied oxidizers is consumed for metallic oxidation, with only a fraction reacting with melt carbon to yield the analyzed carbon oxides. At every stage of decarburization any imbalance is immediately detected and can be corrected by altering one or more of the factors listed previously in a manner to be elaborated upon in the following discussion.

(a) Dynamic control using mixed gases

Since the carbon content that can be attained without metallic (e.g. chromium) oxidation during decarburization at a given temperature is a function of the partial pressure of carbon monoxide in the evolved gas bubbles, it is apparent that the CO partial pressure can be varied by incorporating in the injected gas stream an inert component which does not enter into any chemical reaction. The inert gases as well as hydrogen and nitrogen can usefully serve this purpose during decarburization. Active oxidizing gases that are generally employed for carbon removal are oxygen, steam and carbon dioxide. By adequate adjustment of the proportions of these gases in the input stream, CO at a predetermined partial pressure can be generated.

The process of dynamically-controlled mixed gas decarburization of steels can be suitably performed in a reactor such as a BOF or other container equipped with a means for input-gas and off-gas measurements. The molten steel is tapped into this vessel and held at a known temperature. FIG. 1 is an illustration of a typical process employing mixed gases. Prior to its entry into the vessel,

the gas is measured as to flow rate and analyzed to give an instantaneous reading of its composition. Simultaneously, a sample of the gaseous reaction product is analyzed as previously described, and its oxygen equivalent determined. Assuming 100% carbon-oxygen reaction efficiency, as well as a constant melt temperature of 3000° F., the results of FIG. 1 are obtained for oxygen-argon decarburization of an 18% chromium steel bath. If, for example, at time *t*, the input gas is analyzed at greater than 40% oxygen, the decarburization will continue as shown on the graph, but in addition, the excess oxygen will be applied towards metallic oxidation. This condition will be immediately indicated by a drop in carbon-oxygen reaction efficiency to a value below 100%, and this in turn would call for an increase in the proportion of inert component of the input gas stream. When the balance has been restored, the process efficiency will revert to 100%. The illustrated process assumes a constant total gas flow rate and constant temperature. Deviation from these ideal conditions does not alter the basic concepts described. In either case, input and off-gas analysis serves as an indicator of the efficiency of the reaction.

The example illustrated in FIG. 1 is a process involving stepwise reductions in the oxygen content of the injected gas stream. By adopting infinitesimally small steps, a continuous curve is obtained. Such a curve is adaptable to suitable control devices to supply mixed gases according to the specified schedule. The process according to this schedule is the most efficient since it involves the use of the minimum quantity of inert gases for the amount of carbon removed, and also results in the minimum process time.

(b) Dynamic control through ambient pressure variations

The carbon monoxide partial pressure in the evolved gas bubbles, and consequently, the attainable carbon level in equilibrium with a given bath chromium and temperature, can be varied by means of the ambient pressure around the melt. A pressure-controlled process requires the gas injection, metering and analyzing devices described in (a) above. But in addition, the reactor vessel is equipped with a lid to facilitate its evacuation. The means of evacuation can be pumps, ejectors or any such vacuum-generating equipments. Unlike mixed-gas decarburization, the decarburization process can be accomplished using either oxygen alone or oxygen-inert gas mixtures.

A pressure reduction sequence along with the decarburization path at 3000° F. is illustrated in FIG. 2 for a one ton bath of 18% chromium steel employing 30 s.c.f.m. of oxygen. The scheme illustrated assumes that the gas pumping capacity of the evacuation equipment is unlimited at all pressure ranges. If the pumping capacity of the system involved decreases as the pressure within the vacuum chamber decreases, a continuous reduction of the decarburizing gas flow rate in accordance with the capacity of the pumps is required.

As in example (a), an increase of the melt ambient pressure results in both chromium oxidation and reduction of reaction efficiency. Such a situation is immediately sensed by the off-gas analysis and compensated for by the commensurate amount of pressure reduction until optimum efficiency is re-established. Also as in example (a), the pressure reduction when made smoothly continuous, rather than in steps, further increases the efficiency of the process and reduces the process time.

(c) Dynamic control through temperature variation

The application of this technique is predicated on the fact that at a given carbon monoxide partial pressure and bath chromium content, a lower carbon content can be attained in a bath at higher temperatures. The dynamic variation of temperature employs the same gas injection, metering, and analyzing devices as previously described. Either oxygen or oxygen-diluent gas mixtures can be em-

ployed. Temperature variations are achieved by one or more of the following means: induction heating of the bath, gas heating with carbonaceous fuels such as employed in the open hearth, plasma heating, electron beam heating, injection of oxygen into the bath to react exothermically with an element such as silicon which is easier to oxidize than carbon, or by any other suitable means. The bath temperature can be continuously monitored with the aid of such devices as thermocouples or optical pyrometers. In those instances where carbonaceous fuels are used, the off-gas analysis includes the additional carbon oxides due to the heat source. The proportion of this component in the off-gases is computed from a knowledge of the combustion rate on the bath.

FIG. 3 illustrates a decarburization process, for a one ton 18% chromium heat, decarburized with oxygen at 30 s.c.f.m., and which employs the concept of dynamic control via temperature variations. As in the previous illustrations, an imbalance between input and output oxygen is indicated by the gas analyzing devices. Such imbalance, denoted by an oxygen utilization efficiency of less than 100%, is then off-set by an increase in melt temperature accomplished by one or more of the means previously indicated.

The application of temperature-controlled dynamic balance in decarburization, as in FIG. 3, requires a reactor vessel having a lining capable of withstanding the relatively high temperatures indicated. In practice however, the lower the range of temperatures involved, the more economical the process and lower temperatures are possible by using a combination of temperature, ambient pressure and gas mixture controls.

(d) Dynamic control through gas-metal surface area variations

It is commonly known that the carbon-oxygen reaction occurs at the metal-gas interface. Furthermore, the rate of decarburization in steels is directly proportional to the gas-metal surface area. The efficiency of oxygen consumption, therefore, can be controlled by varying the available gas-metal contact area.

The gas analyzing and efficiency determining devices employed in the application of this embodiment are the same as those described previously. In addition, means for varying gas-metal contact area include (1) sub-surface gas injection resulting in the generation of small gas bubbles which furnish a large surface area, (2) mechanical or (3) induction stirring to continuously expose fresh metal surface to the decarburizing gases, etc.

It is apparent from the above that various changes and modifications are possible in practicing the invention.

Thus, for example, it may be sometimes desirable, usually in making plain carbon steel, to allow some metal oxidation. In alloy steel making, it is generally desirable to avoid oxidation of expensive alloying elements. A convenient technique to measure carbon removal efficiency is by the following determination:

Percent carbon removal efficiency

$$= \frac{\text{Rate of oxygen consumption by carbon}}{\text{Rate of total input oxygen}} \times 100$$

To avoid any metallic loss, the carbon removal efficiency must be equal to or greater than 100%. If some small metal loss is tolerable, then this factor can be some predetermined lower value such as 75-85%.

I claim:

1. In the method of decarburizing molten steel containing metal values which it is desired to avoid the oxidation of, and wherein oxygen is introduced to the steel to react with carbon contained therein, the improvement which comprises introducing said oxygen below the surface of said molten steel in a manner which generates gas bubbles of controlled size, measuring the composition and flow rate of input gases, measuring the composition and flow rate of the off-gases to measure the rate of carbon removal from the steel and continuously maintaining a balance between the oxygen input and carbon removal rates in response to the aforementioned measurements by varying, as necessary, the gas-metal contact area.

2. An improvement according to claim 1 wherein the gas-metal contact area is increased by decreasing the size of the gas bubbles.

3. An improvement according to claim 1 wherein the gas-metal contact area is increased by agitation of the steel bath to continuously expose fresh metal surface to said gas.

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