POWER PARTITION CONTROL FOR CONSUMABLE ELECTRODE FURNACES

Assignee: Allegheny Ludlum Steel Corporation, Brackenridge, Pa.
Filed: Dec. 29, 1967
Appl. No.: 694,657

References Cited
UNITED STATES PATENTS
2,230,296 2/1941 Hopkins .................................. 164/52
2,370,467 2/1945 Hopkins .................................. 164/52
2,825,641 3/1958 Beal et al.............................. 164/52
3,271,328 9/1966 Shelton et al........................... 164/52
2,240,405 4/1941 Kinzel................................. 164/52
2,248,628 7/1941 Hopkins.................................. 164/52

FOREIGN PATENTS OR APPLICATIONS
560,260 7/1958 Canada.................................. 164/52

Primary Examiner—J. Spencer Overholser
Assistant Examiner—V. K. Rising
Attorney—Vincent G. Gioia, Howard R. Berkenstock, Jr. and Richard A. Speer

ABSTRACT
System for controlling the power division between the electrode and molten pool in a consumable electrode furnace by the addition of metallic compounds to the melt for the purpose of stabilizing the arc and shifting the power partition and heat distribution between the electrode and molten pool, whereby the heat in the pool is reduced and that generated at the electrode to melt the same is increased.

5 Claims, 1 Drawing Figure
POWER PARTITION CONTROL FOR CONSUMABLE ELECTRODE FURNACES

BACKGROUND OF THE INVENTION

Consumable arc melting furnaces are now well known and usually comprise an electrode of the metal to be melted extending downward into a mold or crucible which receives the molten metal and within which an ingot is formed. The electrode is connected to one terminal of a direct current voltage source, while means are provided for electrically connecting the other terminal of the source to the mold and, hence, to the molten metal. Usually, in starting the melt, a small supply of chips or the like is placed in the mold so that when the arc is struck, such chips are melted to form an initial molten metal supply in the crucible mold. The arc is maintained between the electrode to be melted and the molten pool of metal beneath it such that the end of the electrode is melted due to the heat of the arc. As the electrode is melted, it is deposited in the mold and forms the aforesaid molten pool, the bottom portion of which continuously solidifies as the electrode melts to form an ingot which increases in length, starting from the bottom upwardly. In this process, impurities float to and on top of the molten pool; and assuming that the pool does not solidify during the formation of the ingot, the major portion of the impurities will be excluded from the main body of the ingot.

In the majority of consumable electrode furnaces, the negative terminal of the direct current power supply is connected to the electrode. This arrangement, commonly referred to as "straight polarity", leads to the development of a power partition whereby only a portion of the total power developed results in a heat which consumes the electrode. The remaining power provides heat to the ingot or liquid pool in the ingot. The power partition thus developed — that is, the amount of heat distributed to the anode or cathode, depends upon the alloy or metal being melted. In most steels, that portion of the power represented by the total of the anode and cathode drops results in a power distribution of approximately 40 to 60 percent at the cathode (i.e., the electrode to be melted) with the balance of 60 to 40 percent at the anode. One of the extreme cases is tungsten where the power distribution is such that approximately 90 percent of the power is developed at the anode as compared to 10 percent at the cathode.

Under straight polarity conditions, only that heat developed at the cathode is effective in melting the electrode, while that developed at the anode adds to the superheat in the pool rather than contributing to the actual melting of the electrode. The heat generated at the anode, therefore, results in a deepening of the pool; and this has been shown to result in several disadvantages such as deeper pipe and/or greater difficulty in hot topping ingots. Furthermore, the additional heat at the anode and resulting deepening of the pool makes the ingot more susceptible to segregation (e.g., freckles) and requires a slower melting rate than would be the case if the pool were shallow.

SUMMARY OF THE INVENTION

As an overall object, the present invention seeks to provide a method for increasing the voltage drop at the electrode in a consumable electrode furnace while decreasing the voltage drop and excessive superheating at the pool beneath the electrode.

More specifically, an object of the invention is to provide a method for increasing power concentration at the electrode of a consumable electrode furnace while decreasing the power concentration at the molten pool beneath it. This is achieved by the addition of a metallic compound to the pool and by reversing normal polarity of a direct current potential applied between the electrode and the mold such that the mold is negative with respect to the electrode. This is in contrast to conventional arc furnaces wherein the electrode is negative with respect to the mold.

Another object of the invention is to provide a method of the type described wherein the metallic compound added to the molten pool is a metal oxide selected from the group consisting of barium oxide, calcium oxide, nickel oxide, thorium oxide, titanium dioxide, lanthanum oxide, strontium oxide, cerium oxide and cesium oxide.

Still another object of the invention is to provide a method for hot topping ingots in a consumable arc furnace wherein the electrode is negative with respect to the molten pool beneath it, and wherein a metallic oxide is added to the molten pool immediately before hot topping begins. This signals the start of hot topping, reduces the arc voltage and stabilizes the arc to achieve ideal hot topping conditions.

In accordance with the invention, a consumable electrode furnace of the type described above is provided wherein an electrode is inserted into a mold and a potential established between the electrode and the mold whereby the heat developed at the electrode will cause it to melt and drop into a molten pool at the bottom of the mold. In constrast to most prior art consumable electrode furnaces, a direct current potential is applied between the electrode and the mold such that the electrode is positive with respect to the mold. Added to the melt is a metal oxide, preferably barium oxide but also including calcium oxide, nickel oxide, strontium oxide, titanium dioxide, lanthanum oxide, thorium oxide, cerium oxide and cesium oxide. Whereas the normal power division between the electrode and the molten pool beneath it is about 50—50, the addition of the metal oxide and reversal of polarity results in 90 percent or more of the heat being generated at the electrode. This not only permits appreciably faster melting rates without the disadvantage of deep molten pools, but also permits the melting operation to be carried out at low pressure levels without incurring destructive damage. Furthermore, yields are increased by reducing hot top losses; and the quality of the resulting ingot is increased.

Preferably, the metal oxide is added to the melt by encasing it within a metal tube which is welded to the side of the electrode such that it melts and deposits the oxide in the molten pool progressively during the entirety of the melting operation. However, if desired, the oxide may be added in the form of a powder or granules during the initial stages of the melting operation or continuously during the melting operation, preferably the latter.

The addition of a metal oxide to the melt can also be used under straight polarity conditions to signal the start of a hot topping operation. In this case, the oxide is preferably encased in a rod welded to the top of the electrode. When the arc reaches the area of the rod, the oxide is freed and drops into the molten pool, thereby stabilizing the arc and reducing arc voltage to achieve ideal hot topping conditions. This permits the current to be reduced to much lower levels than could be tolerated on conventional vacuum melts and results in the ideal condition of little or no melting of the electrode during hot topping.

The above and other objects and features of the invention will become apparent from the following detailed description taken in connection with the accompanying single FIGURE drawing which schematically illustrates one embodiment of the invention.

With reference now to the drawing, a consumable electrode arc furnace is shown and identified generally by the reference numeral 10. The furnace comprises a conductive mold or crucible 12 which may, for example, be fabricated of copper. Covering the upper open end of the mold 12 is a gas-tight housing 14 having a connection 16 to means, not shown, for evacuating chamber 18 formed by the mold 12 and housing 14 covering it. Alternatively, the chamber 18 could be filled with inert gas; however in either case, the metal to be melted is protected from oxidant potential. Surrounding the mold 12 is a water jacket 20 having inlet and outlet ports 22 and 24, respectively, connected thereto. The water jacket 20 is secured to the mold 12 and housing 14 by means of circumferentially spaced bolts 25 and suitable gaskets, substantially as shown.
The mold 12 contains the ingot 26 which solidifies from a molten pool 28 adjacent the lower end of an electrode 30 of the metal to be melted. The electrode 30 is welded as at 32 to a stub shaft 34. The stub shaft 34, in turn, is secured by means of an electrode clamp 36 to the lower end of a vertically reciprocable ram 38. Any type of suitable electrode clamp 36 may be utilized in accordance with the invention; however one illustrative type is shown in U.S. Pat. No. 3,046,319.

While the ram 38 may be reciprocated by any one of a number of different mechanical drives, the system herein illustrated comprises a pair of hourglass rolls 40 and 42, the roll 42 being connected to a drive motor 44 through a mechanical linkage, schematically illustrated by the broken line 46. The motor 44, in turn, is controlled by means of an arc voltage control circuit 48 which may, for example, comprise the usual arc voltage control system wherein the ram 38 is raised or lowered as a function of the total voltage existing across the arc between the bottom of electrode 30 and the molten pool 28.

Surrounding the ram 38 is a ram clamp 50 connected through a first flexible cable or lead 52 to a source of direct current power 54. The other terminal of the power source 54 is connected through a cable or lead 56 to the mold 12. Upon application of a direct current potential between the clamp 50 and the mold 12, an arc or arc plasma 58 is formed between the bottom of the electrode 30 and the molten pool 28.

As was mentioned above, it is usual, in starting the melt, to place a small supply of chips or the like at the bottom of the mold 12 such that when the arc is struck, the chips are melted to form an initial molten metal supply in the crucible mold. After the arc is initially struck, it is maintained between the electrode to be melted and the molten pool beneath it, the electrode being melted due to the heat of the arc. As the electrode is melted, it is moved downwardly by motor 44 to maintain the desired arc gap. The position of the electrode 30 with respect to the ram 28 may be controlled in various ways; however, by way of illustration, the voltage existing between the clamp 50 and mold 12 (i.e., the arc voltage) may be applied to the arc voltage control circuit 48 via leads 60 and 62. As the arc voltage increases, this increase is sensed by circuit 48 which causes motor 44 to drive the ram 38 and electrode 30 downwardly. Conversely, if the voltage between leads 60 and 62 should decrease, indicating a shortening of the arc gap, the motor 44 is caused to drive the ram 38 and electrode 30 upwardly. Instead of using the arc voltage control system described above, however, it is also possible to use a hash control system such as that described in U.S. Pat. Nos. 3,186,043 and 3,187,078. While the control system for the electrode forming part of the present invention, suffice it to say that any suitable control system may be employed which will maintain a desired arc gap between the bottom of the electrode 30 and the molten pool 28.

As was mentioned above, it has been common to connect the direct current power source 54 to the ram 38 and mold 12 such that the electrode 30 is negative with respect to the ingot 26 and molten pool 28. In consumable electrode melting, the term "arc voltage" normally means the total voltage drop across the furnace system. This would be the voltage read on a meter connected between leads 60 and 62. This total arc voltage, however, is divided into parts according to the following equation:

\[ V_a = V_i + V_o + V_e + V_p \]  

where:

- \( V_a \) = total arc voltage existing between leads 60 and 62,
- \( V_i \) = voltage drop at the cathode (i.e., at the lower end of electrode 30 on straight polarity),
- \( V_o \) = voltage drop at the anode (i.e., at the upper surface of the molten pool 28 on straight polarity),
- \( V_e \) = voltage drop in the arc plasma 58, and
- \( V_p \) = resistive voltage drops in the system.

The resistive voltage drops in the system, \( V_p \), includes those voltage drops through leads 52 and 56, the clamp 50, ram 38, clamp 36, the electrode 30 itself and mold 12. In certain cases, these voltage drops may be relatively high due to arcing and heating which occurs at the clamp 50 or electrode clamp 36, for example.

From the foregoing equation, it can be seen that the heat generated in the system is partitioned according to the magnitudes of the individual voltage drops. The heat that is used for melting is developed at the tip of the electrode 30. On straight polarity with the electrode 30 negative with respect to the molten pool 28, this heat would be proportional to the voltage drop, \( V_i \), at the cathode. On reverse polarity with the electrode 30 positive with respect to pool 28, it would represent the voltage drop at the anode. The heat generated at the surface of the molten pool 28 would be represented by either the voltage drop at the cathode or anode, depending upon the polarity used.

As an example of the aforementioned voltage distribution, a 12-inch diameter, high-speed tool steel was vacuum melted on straight polarity (i.e., the electrode negative) under conventional conditions at a total arc voltage, \( V_e \), of 25 volts and arc current of 4,000 amperes with a melt rate of 5 pounds per minute. The resistive voltage drops, \( V_r \), and the voltage drop in the arc plasma, \( V_p \), were determined by driving the electrode slowly into the pool. As the arc gap was shortened, the voltage decreased from the previous 25-volt level. When the voltage reached a value of 23.5 volts, it dropped immediately to a short-circuit value of 1 volt. From this, values of 1 volt for \( V_i \) and 1.5 volts for \( V_e \) can be assigned. Consequently, it is known that the sum of \( V_e + V_i \) by difference is equal to 22.5 volts. Since the voltage drops at the cathode and anode are confined to very small and very high temperature areas, they cannot be measured directly. The voltage drop at the electrode tip, however, can be calculated by the following equation:

\[ MR = \frac{V_i}{I/k} \]

where:

- \( MR \) = melt rate in pounds per minute,
- \( V_i \) = voltage drop at the electrode in volts,
- \( I \) = melting current in amperes, and
- \( k \) = a constant varying with the type of material used. For iron, having an enthalpy at the melting point of 565 BTU's per pound, \( k \) = 9940 watt minutes per pound or approximately 10^4.

Substituting actual values in this equation we find:

\[ 5 = V_i \times 4000/10^4 \]

or \( V_i = 12.5 \) volts.

Since the melt was made under straight polarity conditions with the electrode negative, the value of \( V_i \) is also the value of \( V_r \). Therefore, the voltage drop at the cathode is 12.5 volts and the voltage drop at the anode is 10 volts. The power partition in the melt then results in a heat distribution as follows:

<table>
<thead>
<tr>
<th>Table I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Distribution Table</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>P1=6.00kw=225BTU/minute</td>
</tr>
<tr>
<td>P2=1.50kw=50BTU/minute</td>
</tr>
<tr>
<td>P3=12.5kw=300BTU/minute</td>
</tr>
<tr>
<td>P4=0.00kw=60BTU/minute</td>
</tr>
<tr>
<td>TOTAL=565BTU/minute</td>
</tr>
</tbody>
</table>

The figures shown in the foregoing Table I indicate that approximately 55 percent of the sum of \( P \) and \( P_a \) is generated at the cathode and 45 percent at the anode. Thus, during each minute of melting, 225 BTU's of heat go into heating up the leads 52 and 56, clamp 50, the mold 12 and other elements through which the arc current flows. Also, 340 BTU's per minute are generated in the arc plasma 58. Two thousand
eight hundred forty BTU's per minute are developed at the electrode tip; and it is this heat which actually melts the electrode. The example also shows that 2,250 BTU's per minute are developed in the pool 28. This heat adds to the superheat in the pool and does not contribute to the actual melting of the electrode, except perhaps by radiation from the pool. The heat generated in the pool, therefore, results only in a deepening of the pool with its attendant disadvantages such as deeper pipe and/or greater difficulty in hot topping ingots.

In accordance with the present invention, the heat generated in the pool 28 is reduced and that developed at the tip of the electrode 30 is increased for a given power input by reversing the normal polarity of the electrode with respect to the ingot and by adding to the melt a metallic oxide which is preferably barium oxide but which also can be calcium oxide, nickel oxide, strontium oxide, thorium oxide, titanium dioxide, lanthanum oxide, cerium oxide and cesium oxide. Preferably, the metallic oxide is packed into a tube, identified by the reference numeral 64 in the drawing, formed from the same metal as the electrode 30 itself. After the metallic oxide is packed into the tube 64, its ends are sealed and the tube swaged to consolidate the oxide and form what might be described as an inverse welding rod. Only a single rod may be utilized as shown in the drawing, or two or more rods may be used, depending upon requirements. As the electrode 30 melts, the rod 64 will also melt, thereby freeing the metal oxide which drops into the molten pool 28.

Generally speaking, the effect of the oxide addition on power partition and arc stability is not proportional to its concentration. Heats made at a 0.007 percent oxide addition by weight of the ingot behave similarly to those melted at a 0.15 level. A heat made with 0.0016% BaO showed no effect on the arc. Generally speaking, the oxide addition should be at least 0.005 percent by weight, or enough to achieve the aforesaid power partition.

It must be remembered that the pool 28 is now negative with respect to the electrode 30; and as the electrode drops into the pool it will, of course, be reduced, thereby releasing the metal which, it is theorized, changes the emission characteristics of the cathode such that electrons can more easily leave the cathode. Hence, the voltage and power developed in the pool 28 decreases while that developed at the tip of the electrode 30 increases.

As an example of the invention, an electrode 4½ inches in diameter of Type AISI 321 stainless steel was welded to the bottom of the ram 34 and the power source connected to the ram and the mold such that the mold was negative with respect to the electrode. The metal oxide added was barium oxide; and this was packed into stainless steel tubes of about 0.25 inch outer diameter. The ends of the tubes were sealed and the tubes swaged to 0.125 inch outer diameter, thereby consolidating the barium oxide to produce a barium oxide content of 0.35 gram per inch. Two such rods were welded on the electrode 180° apart. The average melt rate was 3.5 pounds per minute and the vacuum level within the chamber containing the electrode was 1 micron. By driving the electrode down into the molten pool it was found that the resistive voltage drops $V_v$ were 3.5 volts and the voltage across the arc plasma $V_a$ was 1 volt. The total arc voltage $V_i$ was 12.5 volts and, accordingly, the sum of the voltage drops at the anode and cathode ($V_v + V_a$) was 8 volts. Furthermore, from equation 2 given above, we can calculate the voltage drop at the electrode, $V_v$, as follows:

$$V_v = \frac{3.5 \text{ pounds/minute} \times 10^6}{4750 \text{ amperes}} = 7.4 \text{ volts}$$

The electrode voltage, $V_v$, now equals the anode voltage, $V_a$, since the electrode 30 is now positive with respect to the molten pool 28. Accordingly, since the sum of $V_v$ and $V_a$ is 8 volts and since $V_a$ is the voltage developed at the tip of the electrode 30, is 7.4 volts, a voltage of only 0.6 volt is developed at the surface of the molten pool 28. The power distribution is, therefore, as follows:

| P=VxI=16.60 | kW=277 KWH=940 BTU/minute |
| P=1.0Vx750=4.75 | kW=79 KWH=269 BTU/minute |
| P=6Vx4750=286 | kW=407 KWH=161 BTU/minute |
| P=7.4Vx4750=32.20 | kW=588 KWH=2000 BTU/minute |
| P=12.5Vx4750=59.40 | kW=990 KWH=3370 BTU/minute |

From the foregoing Table II, it can be seen that the power partition with the addition of barium oxide is such that 92.5 percent of the heat is generated on the electrode itself with only 7.5 percent generated in the pool, considering only the cathode and anode drop.

An additional heat was melted under the conditions given above except that straight polarity was used with the electrode 30 negative with respect to the molten pool 28. In this case, the barium oxide was added after the ingot had been melted by conventional techniques for 11½ minutes. After the barium oxide addition was made, the electrode stopped melting. The furnace remained on at full power for an additional 55 minutes during which time no melting of the electrode was apparent. Without the oxide addition the electrode would have been consumed rapidly. The voltage drop at the cathode, therefore, was reduced to a value which would not support melting of the electrode.

Improvement in power distribution is also obtained with additions of the other metal oxides enumerated above, although barium oxide has been found to produce the best results. Actual mill trials on 7-inch diameter ingots of D 6-A alloy vacuum melted on reverse polarity with additions of thorium oxide and strontium oxide additions are tabulated in the following Table III.

| TABLE III |
|---|---|---|
| 7C-295 | 7C-410 | 7C-411 |
| (no | Thorium | Strontium |
| oxide | Oxide | Oxide |
| Addition | Addition | Addition |
| Melt Rate lbs/min. | 4.58 | 4.50 | 4.50 |
| Current (amps) | 4500 | 4000 | 4000 |
| $V_v$ | 27.5 | 30.0 | 30.0 |
| $V_a$ | 10.2 | 11.2 | 11.2 |
| $V_v$ | 12.4 | 3.3 | 1.0 |
| $V_a$ | 2.0 | 13.0 | 11.0 |
| $V_v$ | 2.9 | 2.5 | 2.0 |

Note that the cathode voltage (at the pool with reverse polarity) decreases markedly with the additions. Similar results are obtained with calcium oxide, nickel oxide, titanium dioxide, lanthanum oxide, cerium oxide and cesium oxide, with varying degrees of success. For example, calcium oxide does not produce results as good as those produced by thorium and strontium oxides; and nickel oxide and titanium dioxide are poorer than calcium oxide. As a general rule, it can be said that those oxides can be used which are good electron emitters (i.e., those compounds which make it easy for electrons to leave the cathode). It is also feasible to use combinations of the oxides enumerated above.

From the preceding examples, it can be seen that the addition of selected metal oxides and in particular barium oxide can and does alter the power partition existing in the arc zone. This alteration is such that the ratio of power distributed between the anode and cathode reveals that the anode receives the bulk of the heat. However, in order for the invention to achieve the desirable results enumerated above, it is necessary that the electrode 30 be positive with respect to the molten pool 28. If the reverse is true, the barium oxide impedes the melting operation.
While the invention is intended primarily for use in concentrating heat at the tip of the electrode, selected metal oxides can also be used for hot topping on straight polarity where the electrode 30 is negative with respect to the pool 28. In this case, the oxide rods or other suitable addition method could be mounted on the side of the electrode at a point at which it was desired to start the hot top cycle. That is, the rods would be much shorter than rod 64 shown in the drawing and would preferably be welded to the top of the electrode 30. When the arc reaches this area, the nominal arc voltage of 25 volts would be reduced to the 10 to 15 volt level, thus signaling the start of the hot top. The presence of the oxide also stabilizes the arc to such an extent that much lower current levels can be achieved with control. This coupled with the advantage of no electrode burn-off results in ideal hot top conditions.

In addition of barium oxide to the molten pool is also useful as a desulfurizer, ad in one heat of carbon steel, the sulfur was reduced from 0.021 to 0.011. An additional benefit of using barium oxide is in the area of crucible protection. It was determined previously that vacuum consutrode melting on reverse polarity was effective in eliminating freckles in the resulting ingot, but resulted in damage to the crucible wall. It was subsequently shown that the use of argon gas above the bath in a quantity sufficient to pinch the arc away from the crucible wall was sufficient to prevent this crucible damage and at the same time preserve the freckle-free condition. Chemical analyses of a number of heats in which the barium oxide addition was made indicate that the residual barium oxide level is less than 0.01 percent and does not materially affect the characteristics of the resulting ingot.

Although the invention has been shown and described in connection with certain specific embodiments, it will be readily apparent to those skilled in the art that various changes in form and arrangement of parts may be made to suit requirements without departing from the spirit and scope of the invention.

I claim as my invention:

1. In the process of consumable-electrode-forming a cast metal ingot, the steps comprising placing an end of an electrode formed from essentially non-oxide bearing metal within a mold, passing a direct electrical current between the electrode and the mold with the electrode positive with respect to the mold to establish a direct current arc between the bottom of the electrode and the metal below it whereby the electrode is progressively melted from said end and is deposited in the bottom of said mold, the molten metal pool deposited in the mold progressively solidifying to build up an ingot, and during the melting cycle progressively adding to the molten pool from a point adjacent the electrode a metal oxide which governs the characteristics of the arc existing between the end of the electrode and said molten pool but which does not build up a substantial slag formation on the top of the molten pool, the addition of said oxide and the positive polarity of said electrode acting to concentrate the major portion of the heat of the arc at the bottom of the electrode while reducing the heat generated at said molten pool.

2. The process of claim 1 wherein said metal oxide is selected from the group consisting of barium oxide, calcium oxide, nickel oxide, strontium oxide, thorium oxide, titanium dioxide, lanthanum oxide, cerium oxide and cesium oxide.

3. The process of claim 1 wherein said metal oxide comprises barium oxide.

4. The process of claim 1 wherein said metal oxide is added to the molten pool only during hot topping of said ingot.

5. The process of claim 1 including the step of evacuating the space between the end of said electrode and said molten pool whereby said arc exists within a vacuum.