United States Patent [19]

Cooper

[11] **3,908,732**

[45] **Sept. 30, 1975**

[54] **METHODS OF PRODUCING LARGE STEEL INGOTS**

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[73] Assignee: **Heppenstall Company,** Pittsburgh, Pa.

[22] Filed: **Dec. 21, 1973**

[21] Appl. No.: **427,085**

[52] **U.S. Cl.** **164/4;** 29/526.5; 164/52

[51] **Int. Cl.**^{2} **B22D 27/02**

[58] **Field of Search** 164/4, 52, 154, 252; 29/526.5

[56] **References Cited**

UNITED STATES PATENTS

3,603,374	9/1971	Cooper	164/52

FOREIGN PATENTS OR APPLICATIONS

1,153,798	5/1969	United Kingdom	164/52
2,003,607	8/1971	Germany	164/52

Primary Examiner—Robert D. Baldwin
Assistant Examiner—John E. Roethel
Attorney, Agent, or Firm—Buell, Blenko & Ziesenheim

[57] **ABSTRACT**

A method is provided for producing large steel ingots by casting a steel ingot free from sinkhead on the body, removing an axial core lengthwise of the ingot to form a central cavity, melting a steel electrode within the cavity under a fused slag by passing an electrical current through the electrode and solidifying the melt in the cavity. The relative proportions of metal from the cavity wall and the electrode are controlled to provide the desired ingot composition and structure.

7 Claims, 13 Drawing Figures

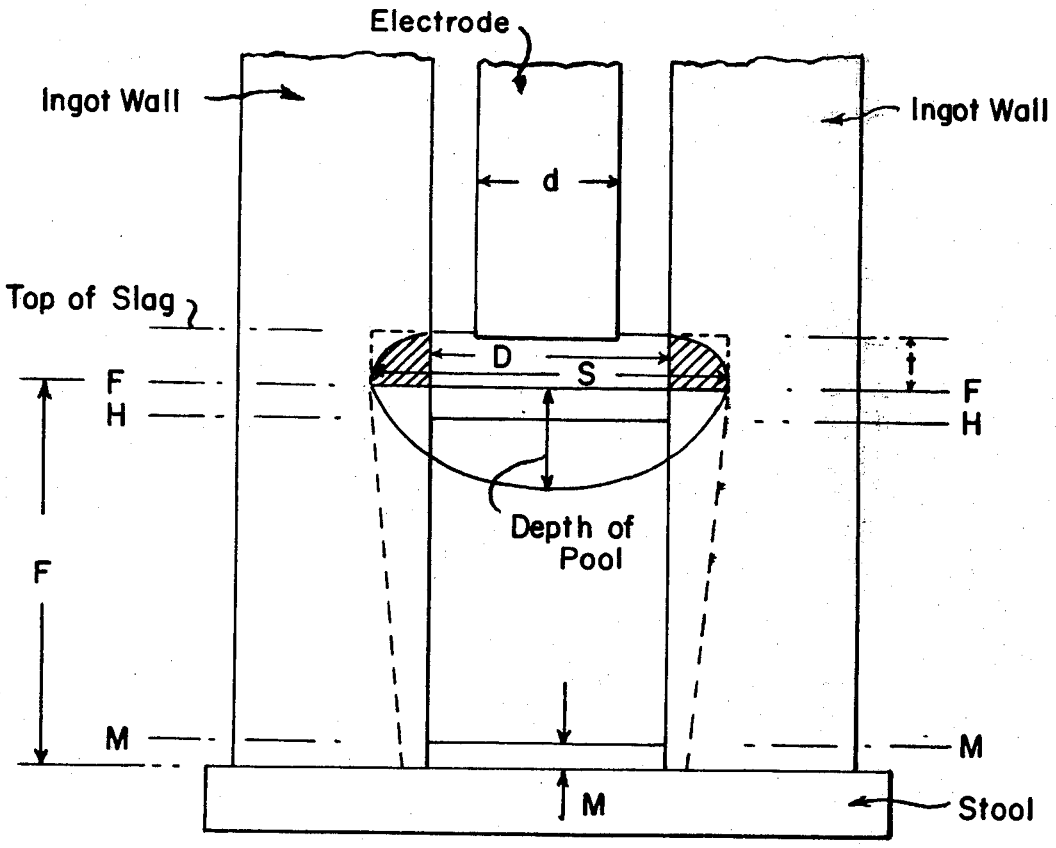


Fig. 1A.

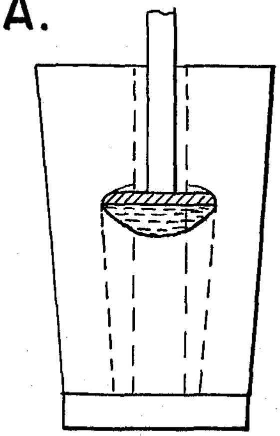


Fig. 1B.

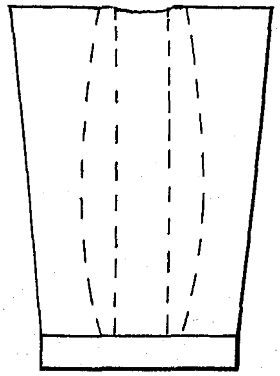


Fig. 2A.

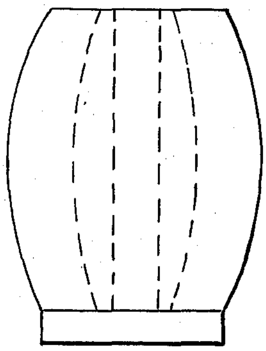


Fig. 2B.

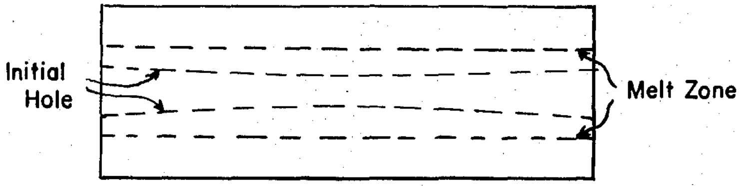


Fig. 11.

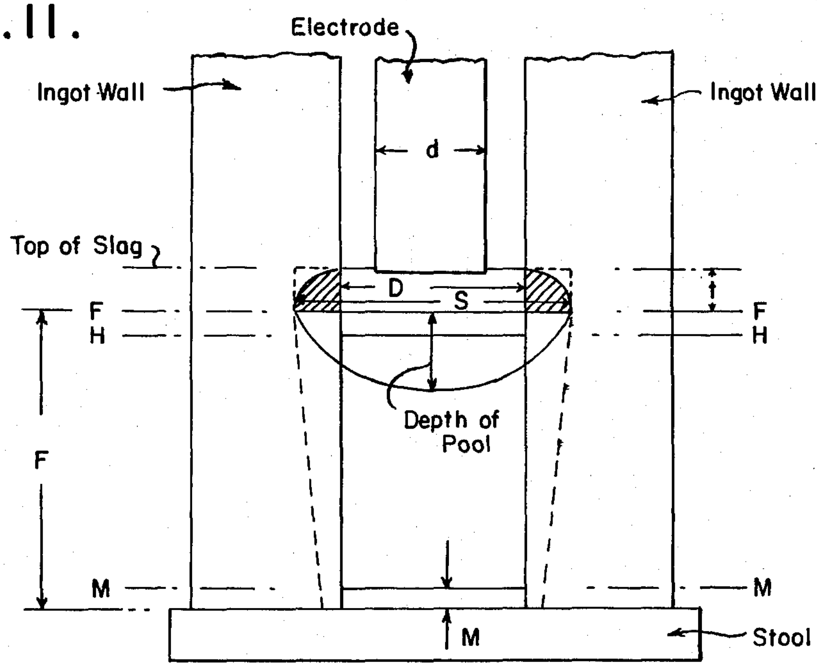


Fig. 3.

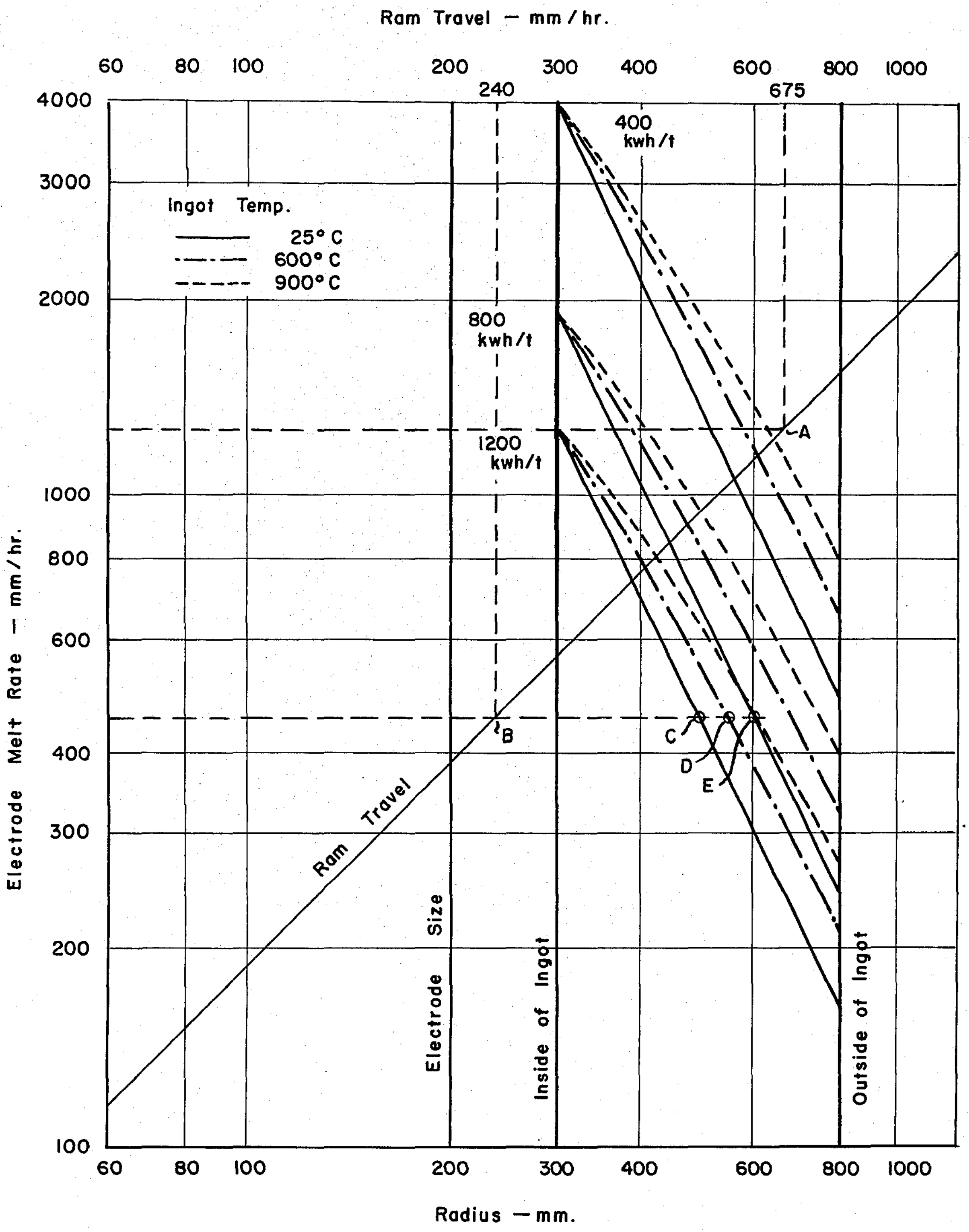

Ram Travel — mm / hr.
60
80
100
200
300
400
600
800
1000
240
675
4000
3000
2000
1000
800
600
400
300
200
100
Electrode Melt Rate — mm / hr.
Ingot Temp.
25° C
600° C
900° C
400 kwh / t
800 kwh / t
1200 kwh / t
A
B
C
D
E
Ram Travel
Electrode Size
Inside of Ingot
Outside of Ingot
Radius — mm.

Fig. 4.

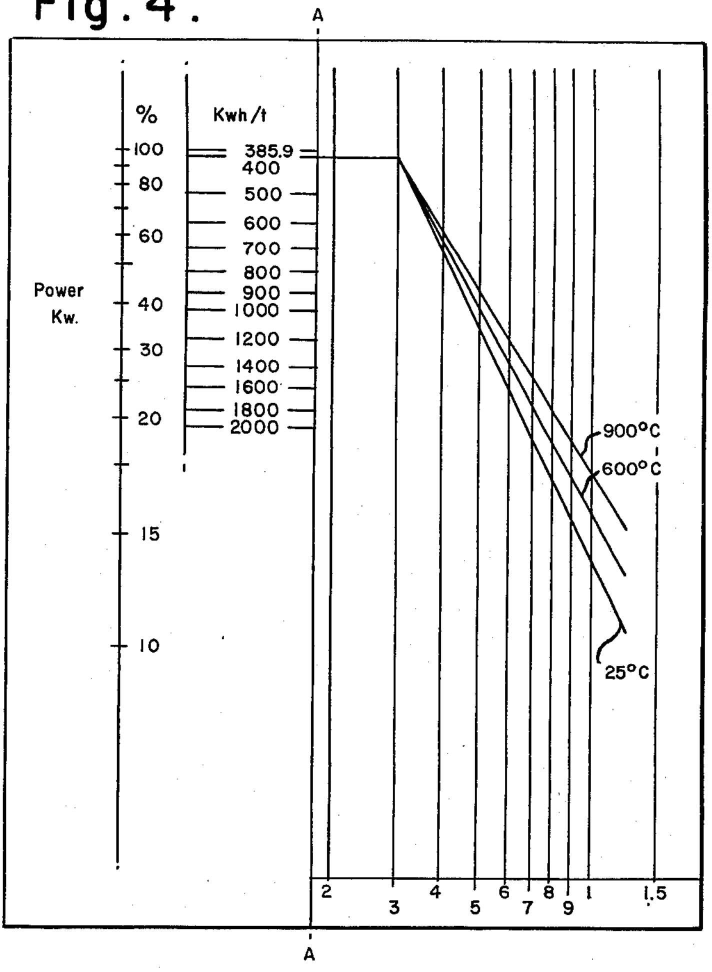


Fig. 6.

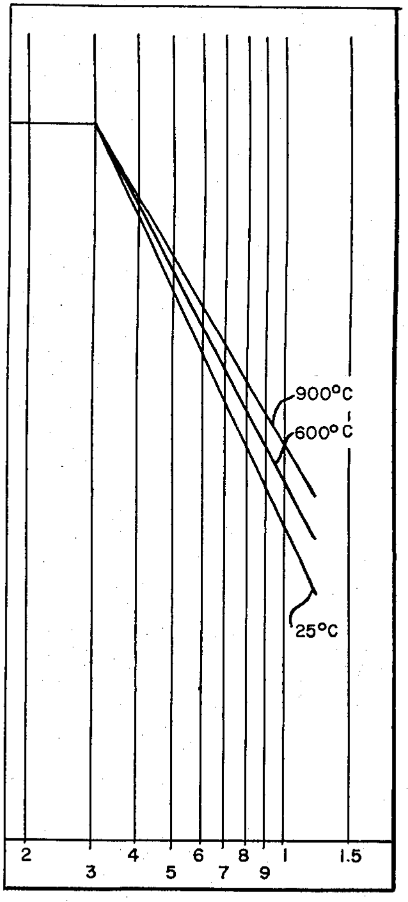


Fig. 5.

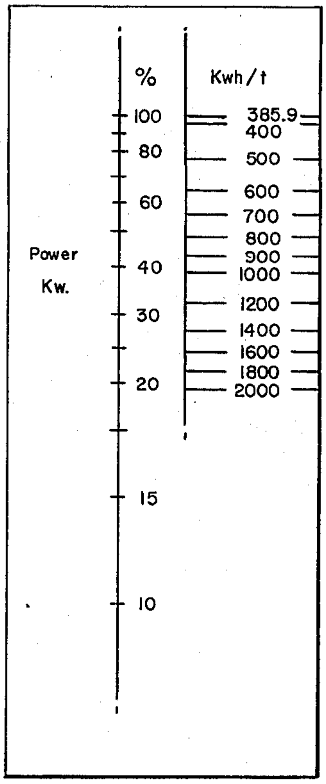
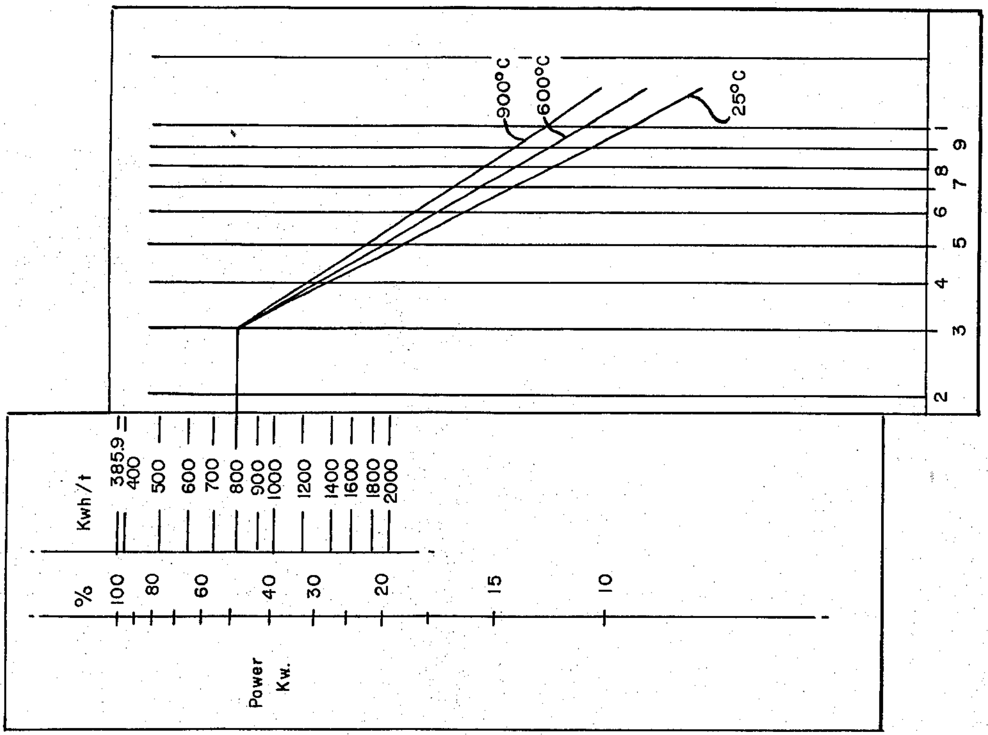


Fig. 8.


900°C
600°C
25°C
1
9
8
7
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3
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Kwh/t
385.9
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700
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1200
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1800
2000
%
100
80
60
40
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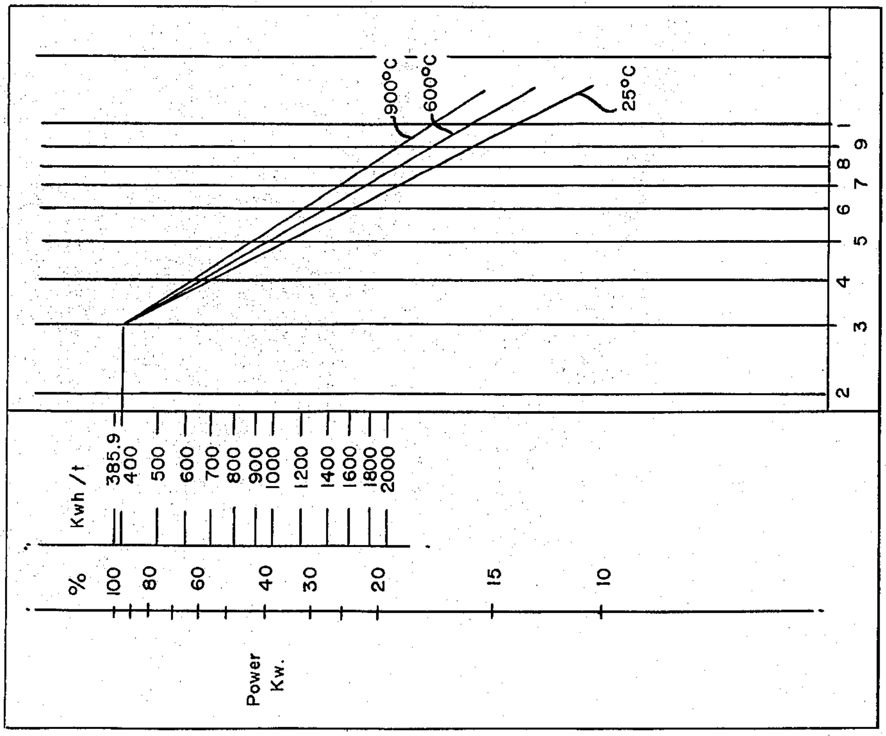
20
15
10
Power
Kw.

Fig. 7.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Kwh/t
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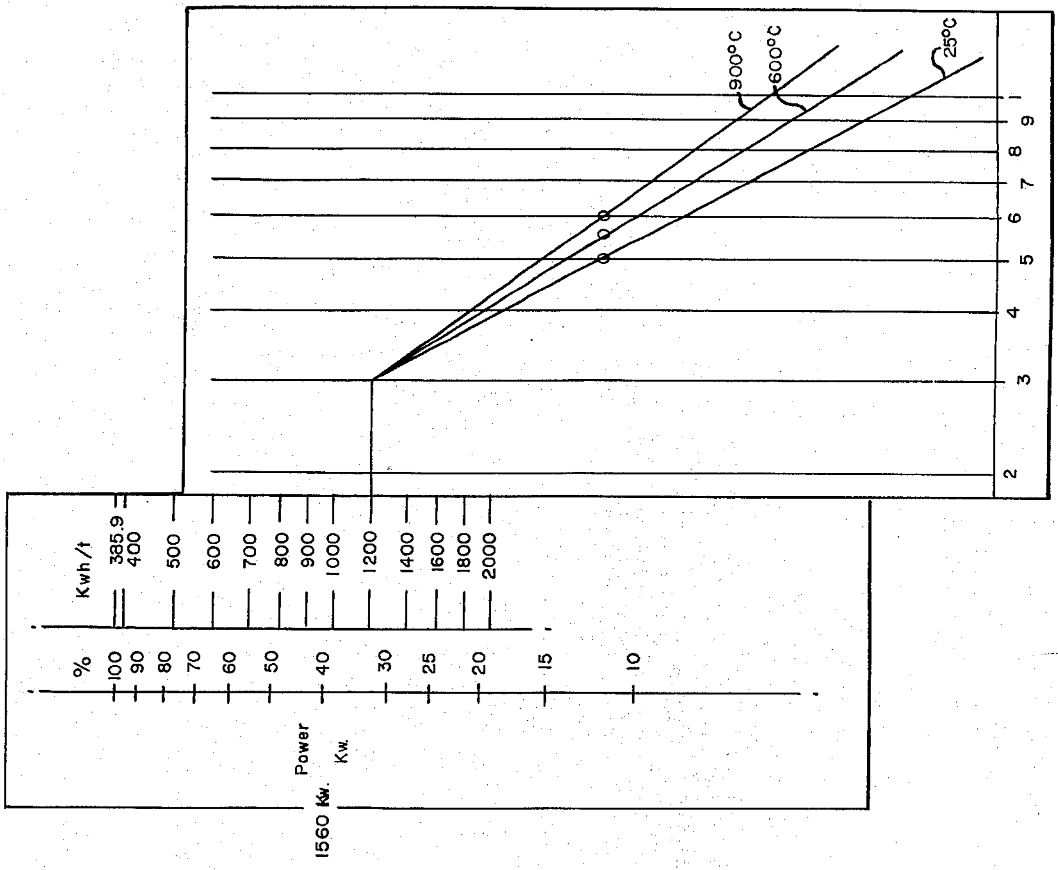
Power
Kw.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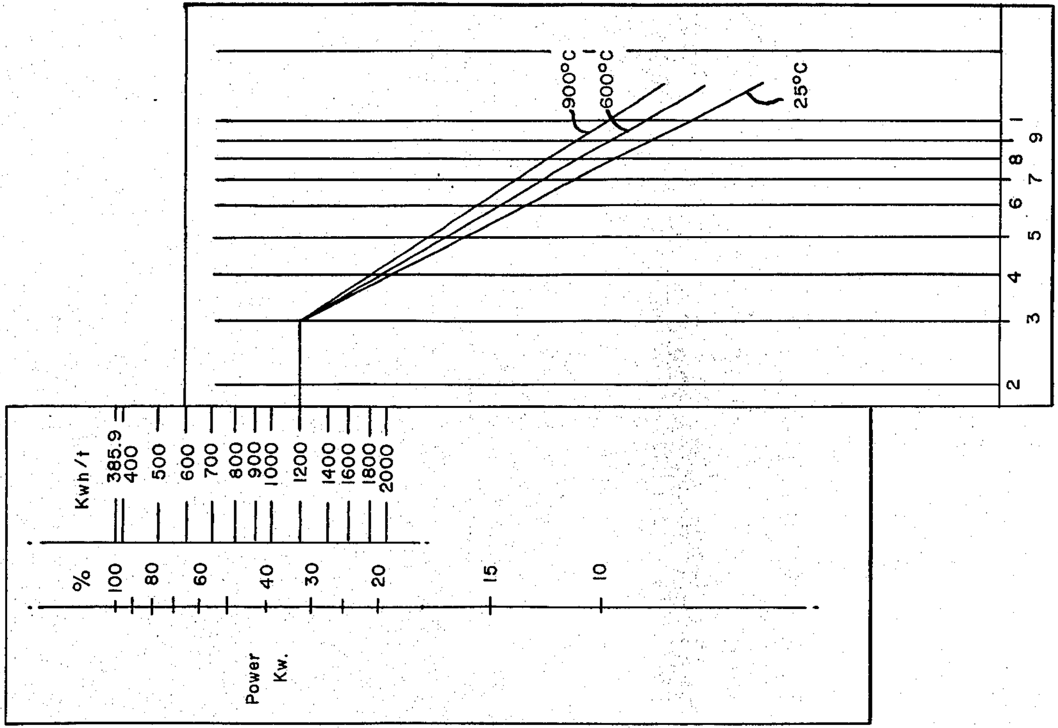
Power
Kw.
1560 Kw.

Fig. 10.


900°C
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Kwh/t
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700
800
900
1000
1200
1400
1600
1800
2000
%
100
80
60
40
30
20
15
10
Power
Kw.

Fig. 9.

METHODS OF PRODUCING LARGE STEEL INGOTS

This invention relates to improvements in the methods of producing large steel ingots, and particularly the method of producing ingots to provide a solid large steel ingot free of the central cavity or pipe common to large ingots, as described initially in the disclosures of United States letters Pat. No. 3,603,374.

In the aforementioned patent, I described the fundamental process of teeming an ingot into a mold with refractory lined or exothermic sinkhead, according to present practices, allowing the steel to solidify, and then forming an axial cavity throughout the full length of the ingot. The patent further describes how the ingot thus formed is set up in a remelting station, with a steel electrode in position, and electroslag remelting the steel electrode, along with a portion of the adjacent wall of the ingot body, to form a central zone of progressively remelted, refined and resolidified steel within the original teemed ingot.

In the practice of producing ingots by this process, it has been found that the yield of product from the initial cast can be improved greatly by eliminating the original refractory lined or exothermic sinkhead and by controlling the extent of melt penetration. Whereas, on large forging steel ingots, it is normal practice to provide a sinkhead as heavy as 30 per cent of the ingot body weight, it is now determined that by eliminating this sinkhead weight, the resulting solid ingot body may then be hot "trepan punched" under the forging press, removing the central core weighing approximately 3 per cent of the ingot body weight. This central trepan punched core contains the initial ingot pipe cavity. The resulting axial hole is then filled by electroslag remelting a steel electrode in the axial hole along with a controlled portion of the side wall of the central hole in the ingot body.

The progressive remelting, refining and resolidification of the central zone by electroslag remelting of the steel electrode and the adjacent portion of the wall of the ingot body provides the desired steel cleanliness and soundness, the same as if the additional sinkhead weight had been used. Thus, the yield of forged product from the poured weight of steel in the ingot body (without an added sinkhead) may be 15 per cent to 20 per cent more than the yield of forged product from the total poured weight of steel in the ingot with the added sinkhead.

FIGS. **1**(A) and **1**(B) show the variability in melt penetration from top to bottom of an ingot using ordinary electroslag melting;

FIGS. **2**(A) and **2**(B) show a method of maintaining uniform wall thickness during electroslag melting;

FIG. **3** shows graphically the relationship for a given power input between steel melted from the electrode and steel melted from the ingot body;

FIG. **4** is a plot of the curves of FIG. **3** for 1560 kw electrical energy and **400** kwh/metric ton and the electrode melt rates equivalent to higher requirements of kwh/metric ton;

FIG. **5** is a plot of the lines to the left of line A—A of FIG. **4**;

FIG. **6** is a plot of the lines to the right of line A—A of FIG. **4**;

FIGS. **7**, **8**, **9** and **10** shows FIGS. **5** and **6** matched along the parting line A—A of FIG. **4** according to different energy systems; and

FIG. **11** is a section through an ingot showing the several parameters taken into consideration in controlling energy input and proportional melt rate.

During the course of electroslag remelting the steel electrode along with the adjacent portion of the ingot wall, it has been observed that the extent to which the melted steel extends into the ingot wall, is not uniform throughout the length of the ingot. The end cooling effect at the bottom end of the ingot, especially when the hollow ingot blank is set upon a water-cooled plate or stool restricts the amount of steel that is melted by the electrically heated slag. In the same manner, heat losses from the top end, by radiation and convection, also tend to limit the amount of steel that is melted. At the mid length portion of the ingot blank, the outside surface area of the ingot is less, for a unit weight, and radiation and convection losses are relatively lower. Consequently, a greater weight of steel is melted by the electrical energy furnished, and the melted zone penetrates more deeply into the ingot wall. This effect is shown in FIGS. I (A) and (B).

Two methods of controlling this extent of melt penetration are described here.

The first method is a simple empirical technique of shaping the outside of the ingot blank, before trepan punching, so that the heat losses will be at least partially equalized, and so that the resulting depth of penetration of the melted zone along the length of the ingot will be progressively in proportion to the cross-sectional dimension of the ingot. On subsequent forging of the ingot to a straight cylindrical section, the resulting remelted central zone will also assume a form that is essentially cylindrical within the resulting forged piece. This is shown in FIGS. **2**(A) and (B). This method is simple and useful, as long as the electrical parameters of current and voltage at the electrode are controlled to provide the proper vertical depth of liquid metal pool under the slag according to the known parameters for electroslag remelting, in order to obtain the desired resolidification characteristics.

The second method of controlling the extent of melt penetration within the ingot blank depends on a continuous balance of energy input, and material melted throughout the course of the remelting cycle. The energy input to be controlled will include the electrical energy through the electrode and the slag, as well as heat supplied to the ingot blank before and during the remelting cycle.

The amount of electrical energy required to melt iron can be determined from calculations for the heat content (expressed as calories/mol) at the ambient temperature and at the temperature achieved after melting. The heat content of liquid iron at 1600° C. (2912° F.) is calculated to be 18,550 calories/mol above the heat content of iron at 25° C. (77° F.). This is equivalent to an electrical energy of 385.9 kwh/metric ton required to raise the temperature from solid iron at 25° C. to the liquid state at 1600° C. By further calculations of the heat contents at other starting temperatures, it is shown that less electrical energies are required to raise the temperature of the solid iron to the liquid state at 1600° C.:

Starting Temperature	Electrical Energy to Heat to Liquid State at 1600° C.
25° C.	385.9 kwh/metric ton
600° C.	287.8 kwh/metric ton
700° C.	270.2 kwh/metric ton
800° C.	243.3 kwh/metric ton
900° C.	222.0 kwh/metric ton

These electrical energy requirements can be related to the weight of steel melted, according to the total electrical energy applied, and the electrical efficiency of the electroslag melting facility. Thus, for example, when a power input of 1560 kw is applied (104 volts at 15,000 amps.), if the system requires 400 kwh to melt a metric ton of steel (slightly more than theoretical value), a total of 3.9 metric tons, or 3900 kg will be melted per hour. If the system is less efficient, and requires a more normal amount of 1200 kwh/metric ton, the melted weight will be 1300 kg per hour.

In a conventional electroslag melting furnace, in a water-cooled crucible, all of this steel melted will come from the electrode, and the rate of melting of the electrode, determined by relationship to the rate of lowering of the electrode clamp (or ram) will reveal the total power requirement for the system in kwh/metric ton.

In this invention, however, not all of the electrical energy is used to melt the electrode. Some energy is used to melt the steel of the ingot wall, according to the energy balance (and heat balance) shown here.

FIG. **3** shows graphically the relationship, for a given power input, between the steel melted from the electrode and the steel melted from the ingot body according to three representative energy requirements of 400, **800**, or 1200 kwh/metric ton according to this invention.

In addition, the effect is shown of the temperature of the ingot body on the amount of ingot that is melted by a given set of conditions. In this particular example the inside of the ingot (axial hole) is 300 mm radius (diameter of 600 mm = 23.6 inches) and the size of the electrode is 205 mm radius (diameter of 410 mm = 16.2 inches).

The graph shows that with the power input of 1560 kw, for a requirement of 1200 kwh/metric ton, the melting rate of 1300 kg/hour is equal to a melting rate, for the 205 mm radius, of 1260 mm per hour to fill the 300 mm radius axial hole without melting any of the ingot wall. This would be indicated by a ram travel (electrode clamp) of 675 mm per hour. (Point A).

An observed ram travel of 240 mm per hour is equivalent to 450 mm per hour electrode melt rate (Point B) for the same power input of 1560 kw, and the electrical energy requirement of 1200 kwh/metric ton. This melting of the electrode consumes only part of the power input (556 kw) and the remainder (1004 kw) is used to melt the portion of the ingot wall, to lesser or greater depth according to the temperature of the steel. If the ingot is at 25° C., the melting zone penetrates to 503 mm radius (Point C), if at 600° C., it penetrates to 550 mm radius (Point D) and if at 900° C., to 610 mm radius (Point E).

To apply this method of energy balance to the control of extent of melt penetration into the ingot, it is necessary first to determine the electrical efficiency of the electroslag remelting facility, taking into account all inductance and other energy losses for the particular

equipment involved. This establishes the electrical energy requirement for the particular equipment, and locates the melt penetration curves relative to the power input.

Direct readings of the ram travel, for the power input, show the amount of penetration of the melt zone into the wall of the ingot blank according to the temperature of the steel.

The rate of ram travel can then be adjusted, either by power drive, or the current setting on the panel, to increase or decrease the rate of melting the electrode as compared with melting the wall of the ingot. In this manner, the energy balance of the system can be monitored constantly, in order to regulate the rate at which the molten steel rises in the axial hole of the ingot, and thereby the total cross-section of liquid steel that is formed within the ingot central zone.

A simple device in the form of a slide rule is described here, that will facilitate the control of the process. The curves of FIG. **3**, for 1560 kw electrical energy input, and 400 kwh/metric ton, are plotted as shown in FIG. **4**. In addition, lines are drawn, showing the electrode melt rates that are equivalent to higher requirements of kwh/metric ton, with the same energy input.

The lines to the left of A—A (FIG. 4) are transferred to one plastic slide, and those to the right of A—A are transferred to another slide. FIGS. **5** and **6** show the image from these two slides. These slides can be matched, along the parting line A—A, according to any known energy requirement of a system, as shown in FIGS. **7, 8** and **9.** If they are placed on a logarithmic graph background, with the interrelationship for ram travel and electrode melt rate, the result of FIG. **10** complies with the graph of FIG. **3,** for 1560 kw, and 1200 kwh/metric ton, for the same size electrode and axial hole.

For different sizes of electrode and axial hole, new master curves of FIG. **4** are prepared and transferred to new slide rules. By preparing and using master curves in this manner, the new process can be controlled easily during the course of the remelting operation, for any size of ingot and electrode.

While the electroslag remelting of the ingot central zone is in progress, it is important to be able to check the extent to which the melt zone is penetrating into the ingot wall, as an additional method of controlling the process.

An approach to determining the melt penetration is based on a material balance. The total metal fill in the axial hole, at any time, is the sum of:

1. The metal melted from the starter plate and the metal chips, plus,
2. The total metal melted from the electrode, plus
3. The metal of the ingot body that is melted by the hot slag above the liquid metal pool.

This is illustrated in FIG. **11.** The metal from the starter plate and the metal chips, is shown as the solid area filling the bottom end of the axial hole, up to the line "M-M". The distance of this fill can be determined by weighing these metals before the start of the melt.

The metal melted from the electrode is shown as filling the axial hole above the line "M-M" up to the line "H-H".

Above the line "H-H", and up to the line "F-F", (the top of the metal fill), the liquid metal within the original axial hole dimension must be assumed to come from the ingot wall that is melted by the hot slag.

Up to the line "F-F," the metal from the ingot wall can be assumed to be "in situ" and need not be accounted for in this material balance.

If we assume the metal melted by the slag to be a cylindrical ring, where

S = Outside diameter of melted slag
D = Diameter of axial hole
t = Depth of slag
H′ = Depth of metal in axial hole between lines H-H and F-F,

then

$(S^2-D^2)t = D^2H'$

In like manner, the height of metal fill from the electrode (as shown in the report for Tests I and II) can be expressed as

H = L-T,

where,

H = Height of ingot fill from electrode
L = Length of electrode melted
T = Ram travel

if

D = Diameter of ingot (axial hole)

and

d = Diameter of electrode,

then

$H = L\, d^2/D^2$

or

$H = T\, d^2/D^2-d^2$

Thus, if M = the height of metal from the starter plate and chips, and F = the total amount of metal fill, then

$$F = M + H + H'$$

Substituting the above formulas, the equation now becomes:

$$F = M + \frac{d^2}{D^2-d^2}\,T + \frac{S^2-D^2}{D^2}\,t$$

From this, it follows that

$$S = D\left[\frac{F + t - M - \frac{d^2}{D^2-d^2}\,T}{t}\right]^{1/2}$$

In this equation, the thickness of the slag layer and the distance up to the top of the metal pool can be determined by an insulated probe from the open top of the ingot. The other terms can be measured directly.

The calculation for the diameter "S" of the liquid slag layer is based on the assumption that the outer surface of the slag (at the slag/metal interface) is that of a vertical cylinder wall. Actually the contact surface is curved (logarithmic or conic: section of an ellipse or a parabola), and the true value for "S" will be slightly greater than determined by the above formula. However, for purposes of practicing the invention, the foregoing formula is sufficiently accurate and provides the necessary control criteria.

In the foregoing specification I have set out certain preferred practices and embodiments of my invention, however, it will be understood that the invention may be otherwise embodied within the scope of the following claims.

I claim:

1. The improved method of producing large steel ingots with higher yield from poured weight to wrought product comprising the steps of

a. Casting a steel ingot to the final desired size, with all of the cast steel weight in the ingot body and free from sinkhead on top of the ingot body,
b. Removing an axial core lengthwise of said cast ingot to form a central cavity,
c. Melting a steel electrode within said central cavity under a fused slag by passing an electrical current through said electrode within the cavity to the ingot,
d. Measuring the thickness of the slag and the distance to the top of the metal pool, and using the known constant dimensions of the ingot and electrode determining the diameter of the molten slag layer and metal pool,
e. Consequently adjusting and controlling the electrical energy input and the heat balance of the electrode and ingot body by controlled preheating of the ingot so as to proportionally melt the steel electrode within the central cavity under the fused slag and at the same time melt a desired uniform portion of the ingot wall and refine the melted portions by reaction with the fused slag; and
f. Solidifying the melted electrode metal within the cavity to form a solid ingot mass.

2. An improved method for producing large steel ingots as claimed in claim **1**, wherein the relative proportion of the steel melted from the electrode and the steel melted from the ingot wall is controlled by varying the material balance in the melting process, and the depth of slag that is positioned on top of the liquid steel within the central cavity.

3. An improved method of producing large steel ingots as claimed in claim **1**, wherein a major portion of the cross-section of the initially cast steel ingot is subjected to the refining reaction of the fused slag, by directing a major portion of the electrical energy input into melting the steel from the ingot wall, while a minor portion of the electrical energy is used to melt the steel electrode, in the course of filling the central cavity.

4. An improved method of producing large steel ingots as claimed in claim **1**, wherein the ingot blank containing the central cavity is preheated to a selected temperature whereby a major portion of the cross-section of the initially cast steel ingot is subjected to the refining action of the fused slag.

5. A method of producing large steel ingots as claimed in claim **1**, wherein the ingot blank containing a central cavity is preheated to a selected temperature and the depth of slag within the cavity is controlled so as to control the relative proportion of ingot sidewall and electrode which is melted.

6. A method of producing large steel ingots as claimed in claim **1**, wherein the relative rate of melting of ingot wall and electrode is controlled by controlling the electrode feed rate.

7. A method of producing large steel ingots as claimed in claim **1**, wherein the relative rate of melting of ingot wall and electrode is controlled by preheating the ingot to a selected temperature and controlling the electrode feed rate.

* * * * *