Sept. 7, 1965 M. C. FLEMINGS, JR., ETAL **3,204,301**

CASTING PROCESS AND APPARATUS FOR OBTAINING UNIDIRECTIONAL SOLIDIFICATION

Filed Oct. 24, 1960 2 Sheets-Sheet 1

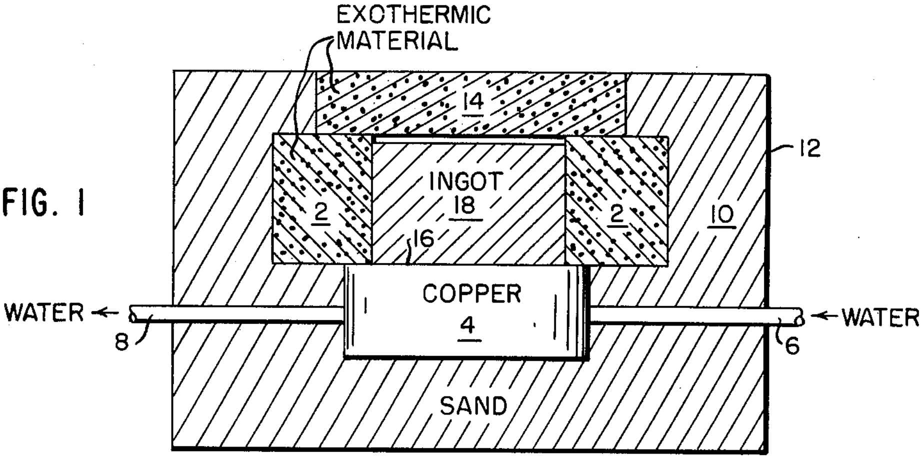

FIG. 1

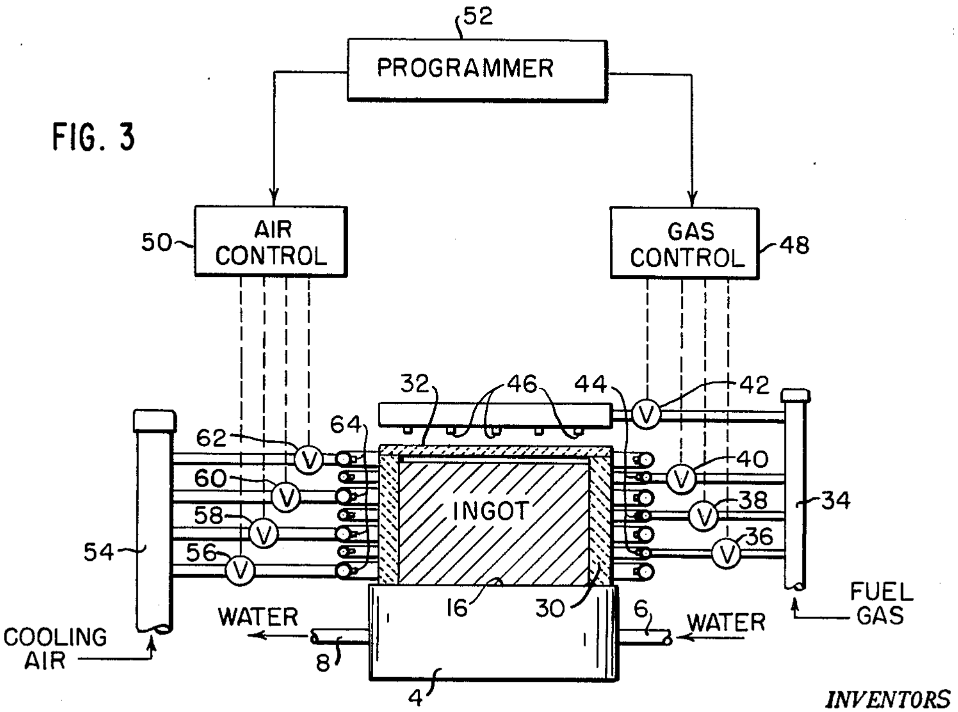

FIG. 3

INVENTORS
MERTON C. FLEMINGS, JR
HOWARD F. TAYLOR
BY Kenway, Jenney & Hildreth
ATTORNEYS

Sept. 7, 1965 M. C. FLEMINGS, JR., ETAL 3,204,301

CASTING PROCESS AND APPARATUS FOR OBTAINING UNIDIRECTIONAL SOLIDIFICATION

Filed Oct. 24, 1960

2 Sheets-Sheet 2

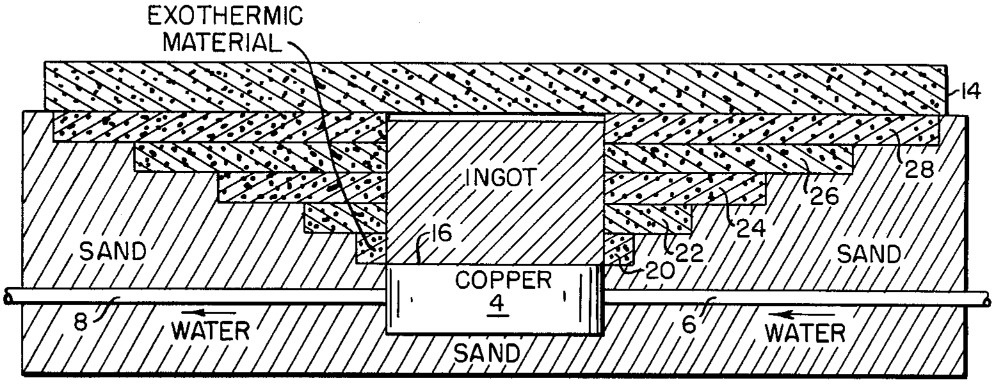

FIG. 2

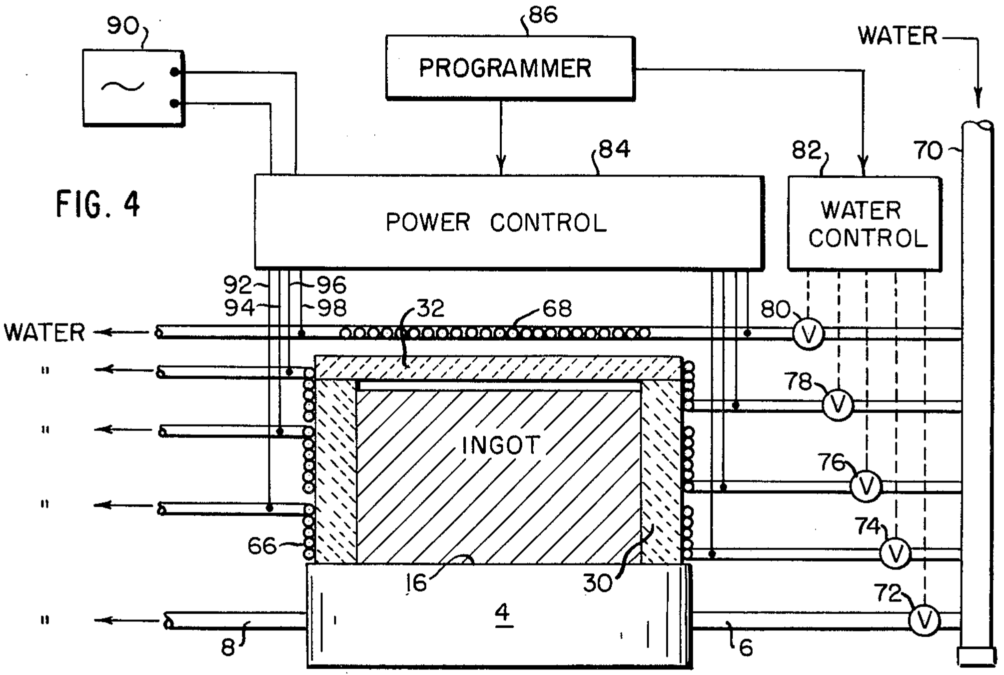

FIG. 4

INVENTORS
MERTON C. FLEMINGS, JR.
HOWARD F. TAYLOR

BY Kenway, Jenney & Hildreth

ATTORNEYS

United States Patent Office

3,204,301
Patented Sept. 7, 1965

3,204,301

CASTING PROCESS AND APPARATUS FOR OBTAINING UNIDIRECTIONAL SOLIDIFICATION

Merton C. Flemings, Jr., Lexington, and Howard F. Taylor, Belmont, Mass., assignors, by mesne assignments, to M. C. Flemings, Jr., and Edith L. Taylor, executrix of said Howard F. Taylor, deceased

Filed Oct. 24, 1960, Ser. No. 131,700
6 Claims. (Cl. 22—74)
(Filed under Rule 47(a) and 35 U.S.C. 116)

This invention relates to methods for casting metal ingots and more specifically to methods wherein the cooling is carefully controlled to optimize properties of the cast ingot.

In conventional ingot-making processes, liquid metal is poured from ladles into metal or refractory molds at the conclusion of melting and deoxidation processes. With fully killed steels, the resulting ingot consists of a surface of fine "chill" grains, a columnar zone of crystallization along the mold walls, a central zone containing substantial amounts of non-metallic inclusions and porosity, and a pipe or large shrinkage void in the region that was last to solidify. Generally, ingot molds are designed to minimize the length of the pipe since this portion of the ingot must be removed and discarded as scrap. The mold is usually of cylindrical or square cross section with varying arrangements of taper or flutes on the vertical faces. Through the use of such tapering, fluting, and hot topping, an attempt is made to concentrate metal shrinkage in one portion of the ingot. However, even with the use of all the conventional techniques, a substantial fraction of the killed steel ingot must be discarded.

In addition, since the central zone of the casting is not removed, further working of such ingots in conventional rolling, forging, or other processing distributes the porosity and inclusions through the final product. Long lines of inclusions in rolled stock known as stringers arise in this way.

It is, therefore, an object of this invention to produce metal ingots with increased ratio of the weight of usable metal to the total weight poured in an ingot mold.

A further object is to produce an ingot with increased chemical homogeneity.

A further object is to produce ingots of improved soundness.

A further object is to produce ingots with a minimum of non-metallic inclusions.

A still further object is to segregate chemical impurities in the portion of the ingot to be discarded.

These and other objects are achieved in a process wherein most of the heat transfer during the cooling of the casting takes place through one surface, resulting in "unidirectional" solidification. More particularly, the process involves maintaining all surfaces of the mold except one at substantially the temperature of melting steel and removing heat through the one remaining surface.

FIGURE 1 is a cross-sectional view of a mold adapted for use with the process of this invention and employing exothermic material.

FIGURE 2 is a cross-sectional view of a mold adapted for use with the process of this invention employing exothermic material.

FIGURE 3 is a cross-sectional view of a mold adapted for use with the process of this invention employing gas heating.

FIGURE 4 is a cross-sectional view of a mold adapted for use with the process of this invention employing electrical heating.

Referring to FIGURE 1, a mold suitable for use with the process of this invention is shown. The main inner body 2 of the mold is composed of exothermic material. Exomold E, a proprietary compound sold by Exomet, Inc., of Conneaut, Ohio, for use if steel is to be cast, is a suitable material.

Exothermic materials suitable for use with steel are normally composed of iron oxide, aluminum and a binder such as sand. An effective burning temperature of about 3,000° F. and a structurally stable composition results from such mixtures. The effective burning temperature can be made to match other casting materials by varying the percentage of binder used and by using other ingredients, such as magnesium.

The bottom inner portion 4 of the mold is formed of a copper block. Water for cooling block 4 is supplied through lines 6 and 8. The inner mold pieces are placed within the sand 10 of a conventional mold box 12.

The casting steps are as follows:

First, the molten metal, steel for example, is poured into the cavity formed by the inner mold pieces 2 and 4. Then an exothermic cover 14 is placed on top of inner mold piece 2. The exothermic material of which inner mold pieces 2 and 14 are composed reacts and burns when contacted by the molten steel contained within the cavity. Therefore, the exothermic material provides an essentially perfect insulator for the inner surfaces of mold pieces 2 and 14. As a result, there is substantially no heat flow in either direction through the surfaces. The remaining mold surface 16 of copper block 4 provides, therefore, substantially the only path for the removal of heat from the molten steel within the cavity.

With heat being withdrawn only through surface 16, the molten steel within the cavity solidifies upwardly through the cavity. While it is customary to enlarge the upper portion of an ingot mold to minimize any pipe remaining within the casting, this enlarged portion of the cavity is unnecessary with the process of this invention. In fact, the central void is so effectively reduced that if desired a smaller, rather than larger, upper central section can be employed to ensure more complete filling of the mold by the cooled ingot 18. Normally, however, it will be simpler to design the mold slightly taller than the desired ingot to allow for the shrinkage upon solidification and cooling which occurs with most materials.

Another mold configuration utilizing exothermic material is shown in FIGURE 2. In the embodiment of FIGURE 2, the interior diameter of the mold is uniform. The exterior, however, is formed of a series of rings 20, 22, 24, 26 and 28 whose diameters increase with their distance away from the cooling surface 16. Thus, in the areas requiring temperature isolation for the longest period of time, a greater amount of exothermic material is provided. Instead of the series of rings, a single piece of varying thickness could be used. The casting operation is identical to that described in connection with FIGURE 1. That is, substantially unidirectional cooling is obtained, the heat being extracted through surface 16 by water-cooled copper block 4.

When exothermic material is used for the mold surfaces, somewhat improved surface texture and purity in the final ingot can be obtained if the exothermic material is pre-ignited. In the above descriptions of casting operations employing the structures of FIGURE 1 and FIGURE 2, the molten metal itself was used to ignite the combustible components of the exothermic materials. Thus, the combustible components are, at least momentarily, burning in contact with the molten metal being cast. When pre-ignition is utilized, a gas flame or other high temperature medium is used to ignite the combustible components of the exothermic material shortly before the molten metal is poured into the mold. While provided in FIGURE 3 for a different purpose, an arrangement such as that of nozzles **46** can serve to preignite the exothermic material.

An alternative structure is shown in FIGURE 3. In this embodiment, the mold comprises a cylindrical portion of conventional refractory material **30** and a refractory top **32**. The bottom surface is again provided by a copper block **4** with water cooling through lines **6** and **8**. However, unlike a conventional mold, pieces **30** and **32** are provided with a source of heat. Gas is fed through line **34** to valves **36, 38, 40** and **42**. These valves supply nozzles **44** and **46** which play flames on the entire exterior surface of pieces **30** and **32**.

The sequence of operations for casting is similar to that for the structure of FIGURE 1. The molten steel is first poured within the mold cavity. Then the cover **32** is placed over the mold. The nozzles **44** and **46** are supplied with gas and ignited to produce a temperature on the exterior surfaces of mold pieces **30** and **32** which almost equals that of the molten steel within. Since the inside and outside temperatures of pieces **30** and **32** are substantially identical, little heat transfer takes place through these portions of the mold. The bottom, however, composed of surface **16** of copper block **4** is cooled by the water supplied by lines **6** and **8**. Therefore, as before, substantially all the heat transfer takes place through the lower surface and the steel solidifies from surface **16** upwards.

While satisfactory castings may be obtained from the structure of FIGURE 3 utilizing only those portions described above, increased control of the casting process is possible if additional control means are used. Valve controller **48** is provided to control the gas valves and valve controller **50** is provided to control air valves. Programmer **52** determines the operation of controllers **48** and **50** according to a predetermined sequence. The sequence of casting steps utilizing the controllers is as follows.

First, the mold, except for the copper block **4**, is brought to approximately the temperature of the metal being cast. To accomplish this heating, the programmer **52** directs the valve controller **48**, just prior to pouring the metal, to open valves **36, 38** and **40** to provide flames from nozzles **44** to heat mold piece **30** to approximately the temperature of the metal being cast. At the same time, programmer **52** has directed air controller **50** to maintain all air valves closed. Next, the metal is poured and cover **32** secured in place. The water cooling of surface **16** causes the metal in the lowermost portion to solidify. Solidification continues in a uni-directional manner away from surface **16**.

Then, as the cooled and solidified zone passes up the cylindrical casting, the gas input to nozzles **44** below that zone is terminated and cooling is provided through air nozzles **64**. While sensing means such as thermocouples could be provided to determine the location of the zone of solidification, a programmed sequence for reducing heat input and introducing cooling gives satisfactory results.

An equation which has been found to govern solidification in a unidirectionally solidified ingot is:

$$x=k\sqrt{t+C}$$

where x equals the distance in inches from the chill face to the end of the completely solid metal, k equals a constant dependent primarily on the particular metal being cast, t equals the time in minutes, and C is another constant. Thus, once constants have been determined by experiment for a particular metal, the sequencing of operation for controllers **48** and **50** can be determined for optimum operation. For steel, k is approximately 1, and C is of the order of ½ to 1.

Programmer **52** is furnished with a predetermined program to determine the operation of gas controller **48** and air controller **50** with time. If steel is being cast, gas controller **48** will be ordered to close valves controlling nozzles **44** within approximately the square root of the time in minutes, plus approximately 1 inch from bottom surface **16** of the mold. Thus when approximately ⅓ of the ingot has solidified, the programmer **52** would order gas controller **48** to close valve **36**. At the same time, programmer **52** would direct air controller **50** to open valve **56** to admit cooling air from line **54** to the lowermost nozzles **64**. As the zone of solidification progresses upwards through the ingot, the programmer **52** directs the gas controller **48** to close progressively more gas valves. At the same time the programmer directs air controller **50** to open a correspondingly increasing number of air valves. While the extraction of heat from surfaces below the cooled zone means that the cooling is not completely unidirectional, it is substantially so and the total casting time is decreased due to the increased rate of heat extraction.

FIGURE 4 illustrates another embodiment for practicing this invention in which greater control of the casting process is also available. The lower surface **16** of the mold is, as before, one face of a copper block **4**. The cylindrical portion **30** and the cover **32** are composed of refractory materials, as in the embodiment of FIGURE 3. In the present embodiment, however, heating for these members is supplied by means of induction heating coils **66** and **68** in close thermal contact with cylindrical portion **30** and cover **32** respectively. The induction heating coils are hollow and are provided with cooling water from line **70** under the control of valves **74, 76, 78,** and **80**.

The sequence of casting steps with the embodiment of FIGURE 4 is as follows: First, before pouring is begun, the programmer **86** directs the power controller **84** to apply power from source **90** to induction heating coil supply lines **92, 94** and **96**. At the same time, the programmer **86** directs water controller **82** to open valve **72** which supplies cooling water to the copper block **4**. Thus, prior to pouring, the cylindrical mold portion **30** is heated to approximately the temperature of the metal to be cast. The cooling water applied to the copper block forming lower face **16** of the mold is likewise applied before pouring to prevent damage to the block.

Next, the metal is poured and the cover **32** secured in place. The operation with respect to the ingot itself is similar to that previously described in connection with FIGURE 3. In other words, the water cooling of surface **16** causes the metal in the lower-most portion to solidify. Solidification continues in a unidirectional manner away from surface **16**. Below the zone of solidification the heating is terminated and cooling begun.

In FIGURE 4, induction heating and water rather than gas and air are utilized for heating and cooling respectively. As the zone of cooling progresses through the ingot, the programmer **86** directs the power controller **84** to terminate the application of electric power from source **90** to the induction heating coils **66** below the cooled zone. At the same time, the programmer **86** directs water controller **82** to increase the flow of cooling water through all coils surrounding solidified ingot. For example, if ⅓ of the ingot is solidified, programmer **86** will direct power controller **84** to terminate the application of power from source **90** to those induction heating coils **66** supplied by line **92**. At the same time, the programmer **86** will direct water controller **82** to increase the flow of water through valve **74**, thus applying additional cooling to those coils through which induction heating is no longer being applied. The water flow through the remaining valves **76, 78** and **80** will continue to be only that necessary to keep the induction heating coils from melting.

Although the above descriptions have been with reference to embodiments incorporating material particularly well-suited for casting steel ingots, the processes are applicable to the casting of other metals as well. While the methods are particularly advantageous for killed steel ingots, ingots of increased soundness and chemical uniformly are also obtained with other metals. The particular exothermic material or heating temperatures involved would be chosen to correspond with the melting point of the particular metal being cast.

By way of example, an ingot of steel was cast utilizing an exothermic mold and unidirectional cooling. The particular alloy employed was AISI 4340 steel. Exomold E, a proprietary compound of the Conneaut Company, was used, and the diameter of the ingot in contact with the cooling surface was four inches. An examination of a cross-section through the length of the ingot disclosed extremely uniform structure. The grain structure of the casting was composed almost completely of long columnar dendrites growing perpendicular to the chilled face. Ingots with long columnar grains possess advantagous structural characteristics.

Chemical analysis confirmed the apparent uniformity of the AISI 4340 ingot. The following Table I gives the percentages of various elements in the composition at six distances from the chilled surface **10**, the distances ranging from ¼ inch to 7¾ inches.

Table I

Distance from chilled surface (inches)	Composition Element (weight percent)							
	C	Mn	P	S	Si	Cr	Ni	Mo
¼	.26	.90	.008	.008	.39	.86	1.95	.29
1¾	.26	.92	.009	.011	.40	.89	1.95	.29
3¼	.25	.91	.009	.010	.41	.88	1.95	.29
4¾	.25	.92	.009	.013	.41	.90	1.93	.29
6¼	.25	.90	.009	.013	.42	.88	1.92	.29
7¾	.25	.89	.008	.063	.64	.88	1.89	.29

It will be noted that the percentages of carbon, manganese, phosphorus, chromium, nickel and molybdenum are extremely uniform throughout the entire range. In the case of the harmful elements sulphur and silicon, however, there has been a substantial concentration of these elements in the portion furthest removed from the cooling surface. While the reason for the centration is not known for certain, careful examination of the casting indicates that the impurity elements formed non-metallic inclusions which floated up from the bottom of the ingot during solidification. Thus, in addition to the increased soundness and uniformity produced by unidirectional solidification, non-metallic inclusions which are deleterious to the mechanical properties of ingots and parts made from ingots, can be floated to the uppermost portion of an ingot during solidification. This upper portion of the ingot can then, if desired, be cut off and later remelted and purified.

Table II sets forth the mechanical porperties of test bars cut from AISI 4340 steel ingots produced as described above.

Table II

Testing Direction	Tensile Strength (lbs./in.^{2})	Yield Strength (lbs./in.^{2})	Elongation (percent)	Reduction in Area (percent)
Transverse to grains	292,000	231,000	8.6	23.6
Longitudinal to grains	294,000	244,000	7.9	20.6

It will be noted that the tensile strengths, both transverse to the grains and longitudinal with the columnar grains, are over 290,000 lbs. per square inch, an exceptionally high value for this alloy. Again, with regard to both transverse and longitudinal orientations the yield strength, elongation, and reduction in area are all values exceptionally favorable for castings of this alloy. While the particular figures obtained would be different with different alloys, castings of uniformly high quality can be obtained.

Economic considerations or availability may dictate a choice of materials differing from those described above. With regard to those portions composed of exothermic material, any available material can be used so long as its temperature characteristics substantially match those of the metal being cast. Similarly, where the mold walls are formed of refractory material, any material suitable for use at the temperatures involved may be used. Since substantially no heat flow from the molten material is involved, conductivity is not important, except for embodiments applying cooling to all non-heated surfaces. In those embodiments, metallic molds are advantageous when compatible with the temperature of the metal being cast. While copper is a preferred material for the main cooling surface, any material of good conductivity and stability at the temperature involved may be used. In fact, at the temperatures and heat flows involved with casting steel, steel is substantially the equivalent of copper for block **4**.

While heat application by means of gas flames and induction heating coils has been shown, heat could be applied in any conventional manner, such as by resistance heating or radiant heating. In embodiments employing programmed heating, a minimum number of valves and control lines has been shown for clarity in the drawings.

Those skilled in the metallurgical arts will recognize that considerable variation can be made in specific means involved without departing from the scope of this invention of unidirectional casting.

Having thus described our invention, we claim:

1. A mold for use in casting a steel ingot, comprising fixed bottom and side walls and a separable top wall completely enclosing a mold cavity therebetween, said bottom wall being formed of heat conductive material, said side and top walls being formed of imperforate exothermic material which extends continuously over the sides and top of said cavity when said top wall is in place, whereby molten steel may be poured into said mold with the top wall removed and then said top wall may be set in place to seal said mold cavity, the combustion of said exothermic material preventing loss of heat through said top and side walls to ensure unidirectional solidification of said ingot as heat is withdrawn through said bottom wall.

2. The mold of claim **1**, said exothermic material having a burning temperature of about 3,000° F.

3. The mold of claim **2**, said exothermic material being composed essentially of iron oxide, aluminum, and sand.

4. The mold of claim **1**, said side wall being progressively thicker from said bottom wall to said top wall.

5. The mold of claim **1**, said top wall resting directly upon said side wall and extending laterally substantially beyond said mold cavity.

6. A process for casting a steel ingot having long columnar grains from bottom to top, comprising the steps of pouring molten steel into the open top of a mold cavity having its sides completely closed by exothermic material with a burning temperature of about 3,000° F. and its bottom closed by heat-conductive material fixed with respect to said sides, completely closing said cavity by placing an imperforate cover of said exothermic material on top of said cavity directly upon and continuous with the closed exothermic sides of said cavity to seal said cavity, whereby said exothermic material burns and prevents loss of heat from said steel through the sides and top of said cavity, and withdrawing heat from said steel through said heat-conductive material until said steel has solidified.

References Cited by the Examiner

UNITED STATES PATENTS

1,199,429	9/16	Roth	22—212 XR
1,789,883	1/31	Roth	22—74 XR
1,961,399	6/34	Snook	22—200
2,045,576	6/36	Bedilion	22—216
2,135,465	11/38	Eldred	22—200.1
2,782,476	2/57	Brennan	22—216
2,856,657	10/58	Urmetz	22—147
2,875,483	3/59	Hughes	22—74 XR
2,951,272	9/60	Kiesler	22—212 XR

FOREIGN PATENTS

367,615	2/32	Great Britain.
661,727	11/51	Great Britain.
698,303	10/53	Great Britain.
726,670	3/55	Great Britain.

MARCUS U. LYONS, *Primary Examiner.*

WINSTON A. DOUGLAS, RAY K. WINDHAM, MICHAEL V. BRINDISI, NEDWIN BERGER, ROBERT F. WHITE, *Examiners.*