United States Patent

Copley et al.

[15] **3,690,368**

[45] **Sept. 12, 1972**

[54] **CASTING SINGLE CRYSTAL ARTICLES**

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[21] Appl. No.: **63,738**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 714,722, March 20, 1968, abandoned.

[52] **U.S. Cl.** **164/350,** 164/34, 164/352, 164/361

[51] **Int. Cl.** **B22c 9/04,** B22c 9/22

[58] **Field of Search**..........164/34, 60, 125, 127, 129, 164/322, 350, 352, 361, 362

[56] **References Cited**

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[57] **ABSTRACT**

Apparatus for the formation of single crystal articles by directionally solidified casting techniques which substantially eliminates the formation of heterogeneous discontinuities in the casting.

11 Claims, 6 Drawing Figures

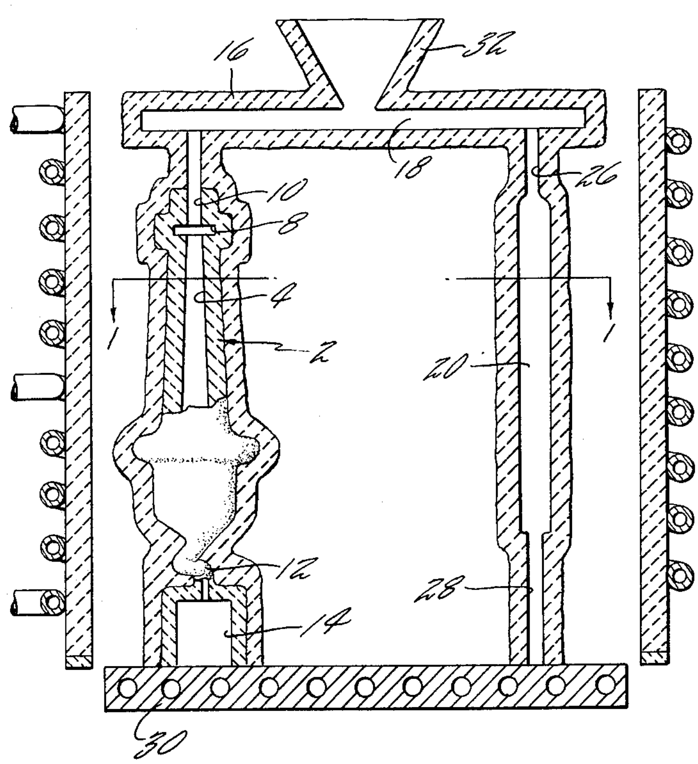

FIG. 1

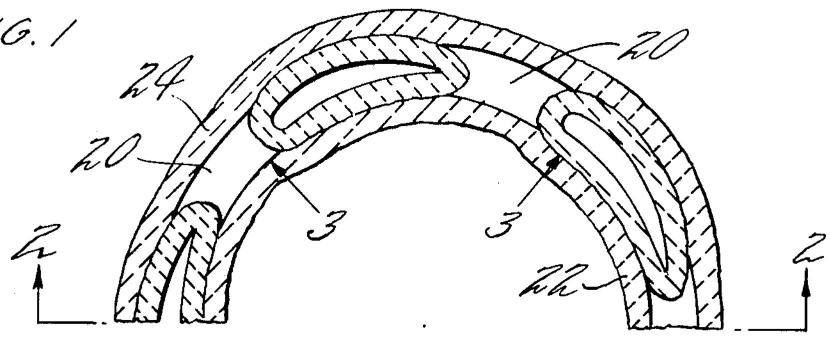

FIG. 2

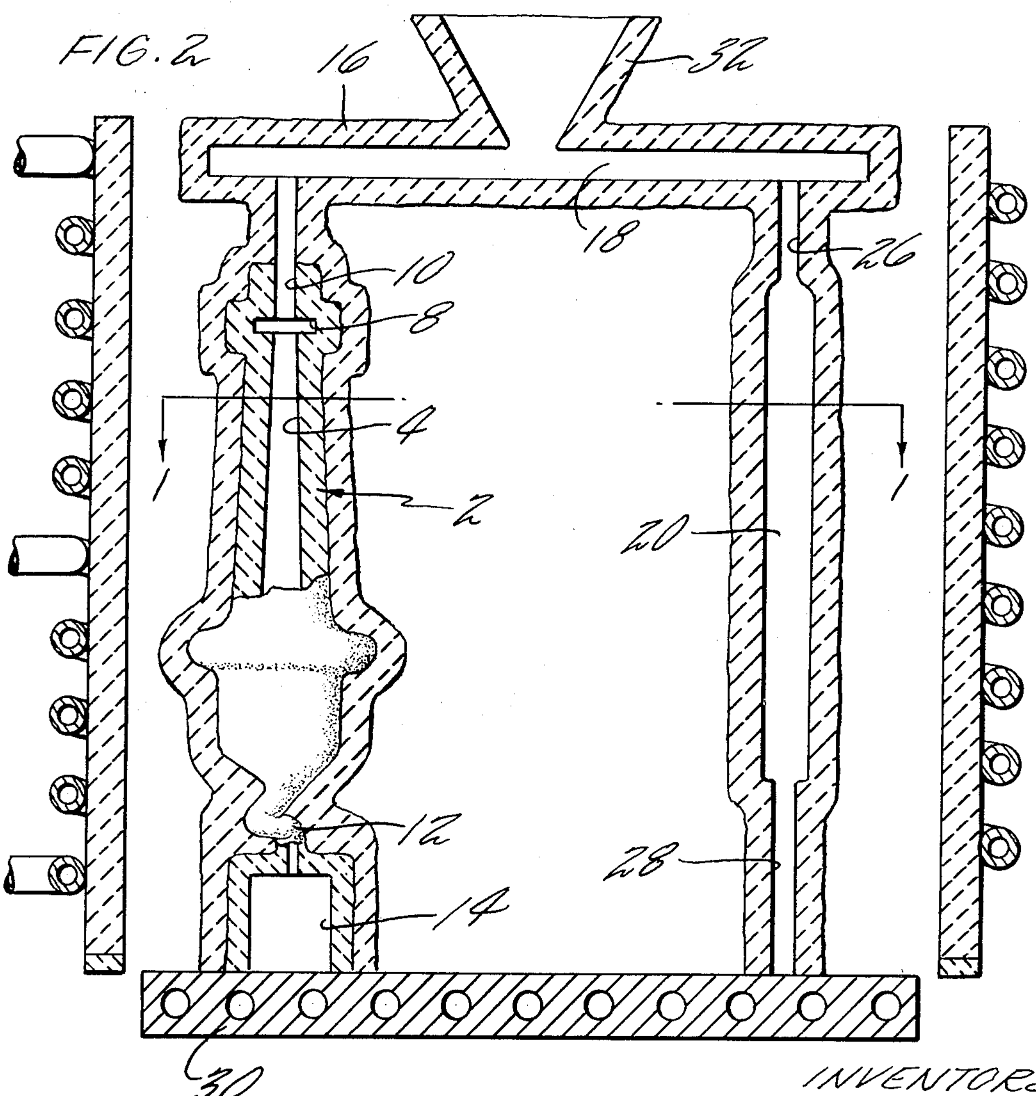

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FIG. 3

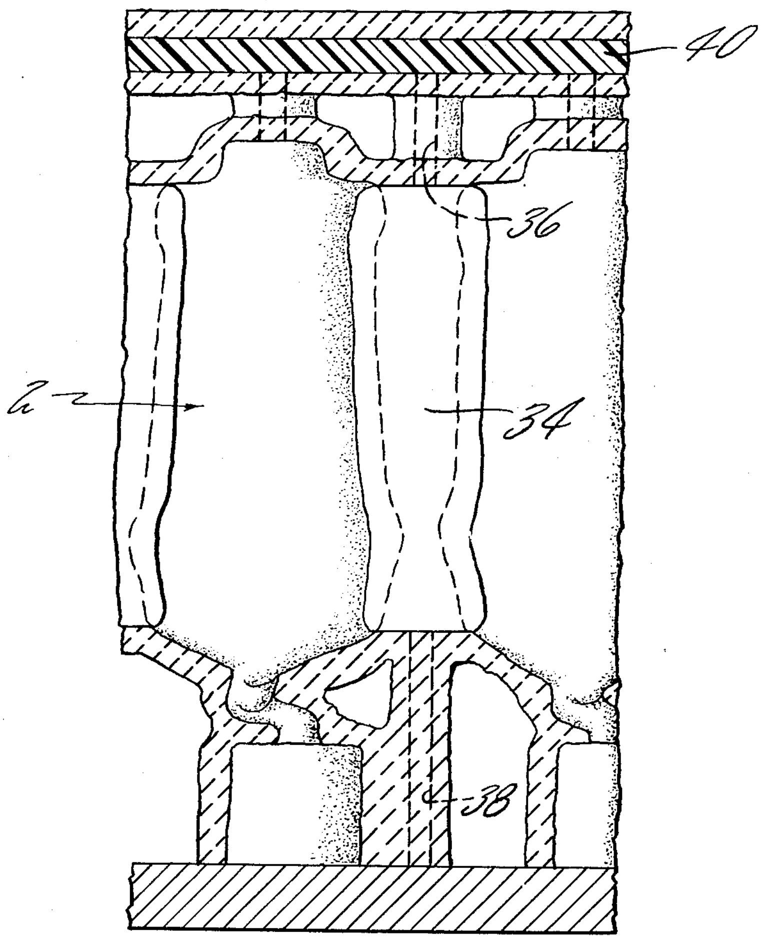


FIG. 4

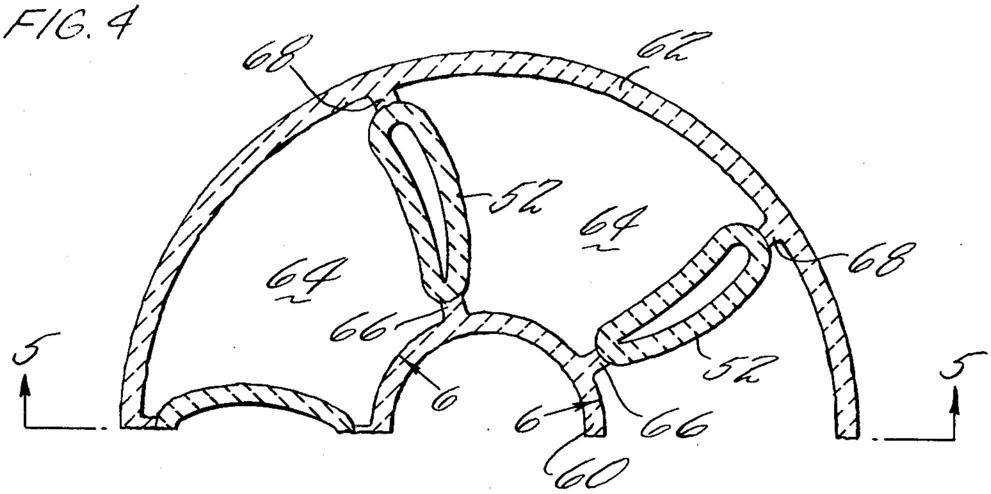


FIG. 5

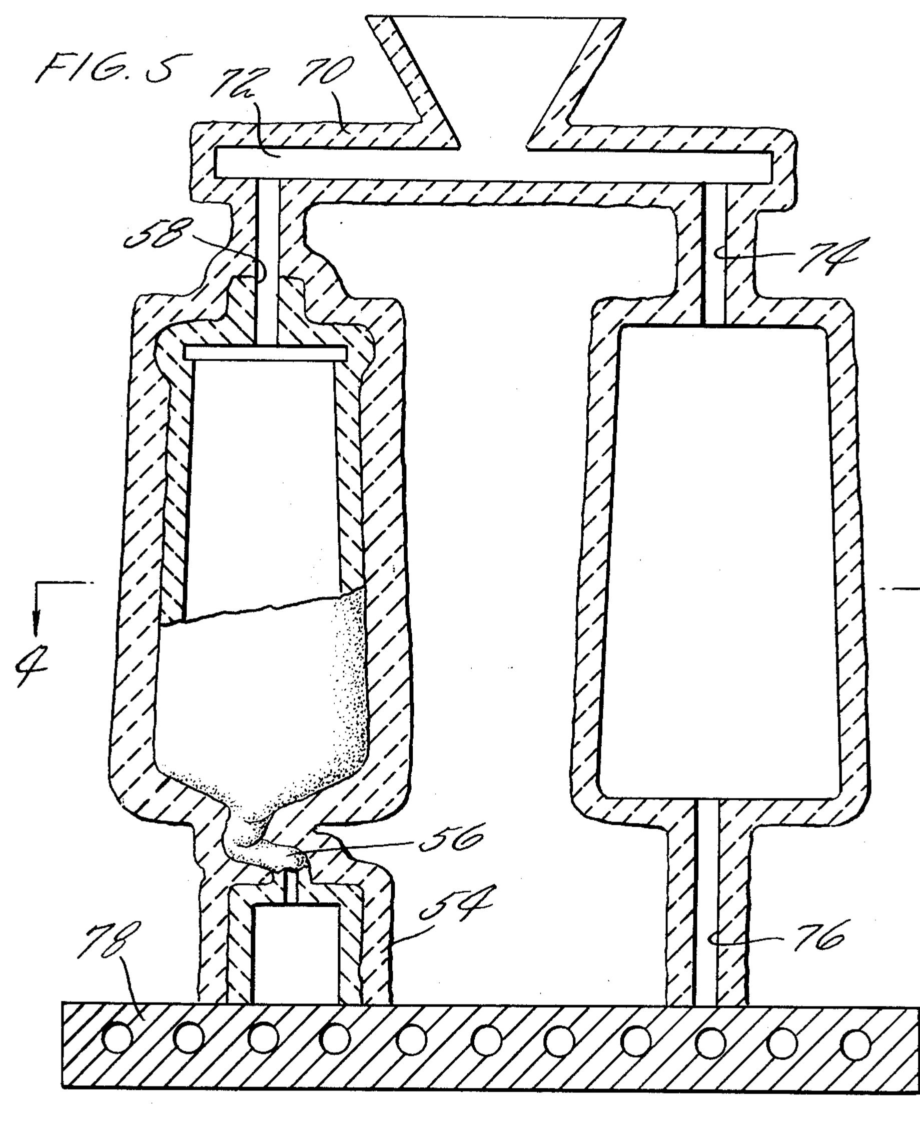
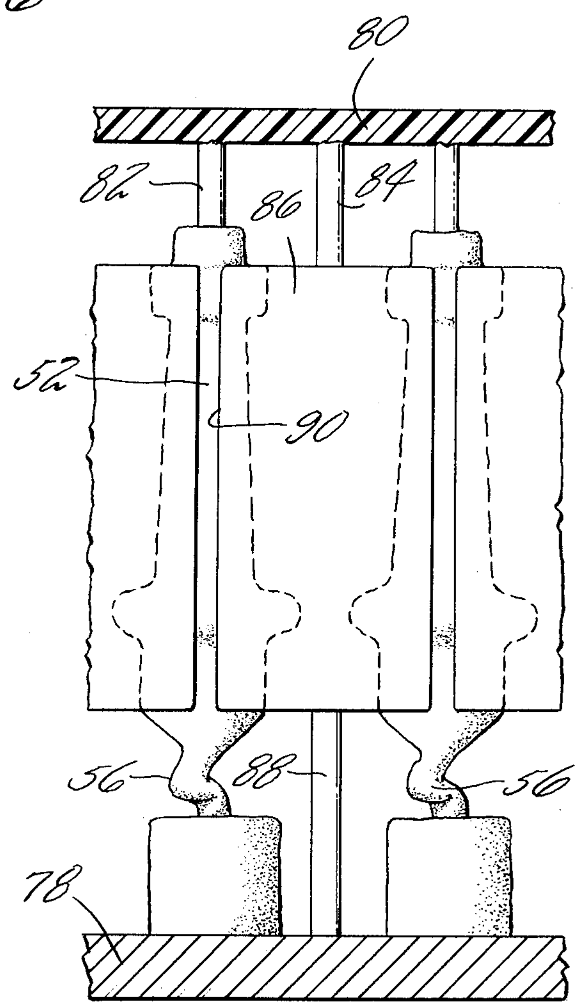


FIG. 6



CASTING SINGLE CRYSTAL ARTICLES

This application is a continuation-in-part of the co-pending application, Ser. No. 714,722, filed Mar. 20, 1968 now abandoned.

This invention relates to the casting of single crystal articles and more specifically to the elimination of stringers of equiaxed grains or freckles at the surface of the single crystal casting.

In casting articles in single crystal form, it is desirable to be able to cast complex as well as simple single crystal shapes that is to say in addition to casting rods or bars it is desirable to produce such complex shapes as turbine blades and vanes with the entire blade or vane including the root airfoil section and at times a shroud all of a single crystal. The complex shaped castings have been limited in the past by the problem of extracting heat at the proper rate since the removal of heat from the solidifying alloy has been accomplished primarily by the conduction of heat from the solidifying alloy through a constriction adjacent to the bottom of the mold. The rate of heat removal through the relatively small cross-section of alloy in the constriction has been low and therefore the thermal gradient and the rate of growth of the crystal have been limited. One method for increasing the heat extraction rate has been described in a co-pending application, Ser. No. 714,743, filed Mar. 20, 1968 for a process for casting single crystal shapes now U.S. Pat. No. 3,543,284. This application has the same assignee as the present application.

One of the problems in obtaining single crystal cast defect free articles is the occurrence of jets which result in the formation of trails of small equiaxed grains. Such convective jets can occur within the mushy zone during solidification. These jets lead to erosion and breakage of the dendrite structure and thus cause the formation of trails of equiaxed grains or "freckles". The jets are a consequence of hydrodynamic instability within the mushy zone and become more pronounced as the liquidus and solidus interfaces become curved or as the mushy zone height increases (i.e. the thermal gradient decreases). Freckle grains are a major defect since they detrimentally effect the mechanical properties of the casting.

SUMMARY OF THE INVENTION

One feature of this invention is an apparatus by which to cast single crystal parts such as turbine blades and vanes without the formation of these trails of equiaxed grains. The elimination of these discontinuities in the surface is obtained by appropriate control of the thermal gradient within the mold, a control of the rate of solidification of the alloy upwardly within the mold and a control of the wall temperature of mold surrounding the article being cast. The latter result is obtained by surrounding the article mold at least in part by a cavity in which a controlled solidification can take place at a selected rate thereby to more effectively control the temperature of the article mold as solidification occurs.

In accordance with the present invention, the article mold is positioned within a surrounding control mold with the latter having one or more casting cavities therein for to receive the control portion of the hot alloy of the control of the alloy which is poured at the same time as the alloy is poured into the article mold. These control cavities are connected through solidification passages to the chill plate and the article mold has a crystal selecting passage in the lower end by which to cause the growth of a single crystal into the article portion of the mold. Although the mold is adapted for the production of a single cast article at one time the construction is more adapted for the gang casting of a plurality of articles at one time and the construction is such that the solidified article may be readily removed from the solidified alloy in the adjacent and partially surrounding control cavities.

The solidification process of the present invention is carried out by positioning the one or several article molds within the surrounding mold and heating the entire assembly to a temperature above the melting point of the alloy. Once the alloy is poured in the mold assembly, directional solidification begins at the chill plate in which the mold assembly rests and the liquid-solid interface moves upwardly from the chill plate in both the bottom of the article mold and in the connectors from the casting cavities to the chill plate. The solidification of the alloy within the casting cavities or control cavities helps to maintain the article mold at the desired temperature during solidification and serves to control the rate of heat removal from the article molds so that the liquid-solid interface of the alloy within the article mold will be retained in a substantially horizontal configuration during the solidification of the alloy through the entire mold. This mold construction favors higher thermal gradients and growth rates needed for the elimination of discontinuities such as trails of equiaxed grains in the cast surface. The rate of heat extraction by the metal in the casting cavities is controlled to a substantial degree by the size of the connector from these casting cavities to the chill plate since area of solidified alloy in these passages is a direct control of the rate of heat transfer to the chill plate.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a horizontal sectional view through a mold assembly.

FIG. 2 is a vertical sectional view substantially along the line 2—2 of FIG. 1.

FIG. 3 is an elevational view of a portion of the mold assembly prior to the formation of the second mold coating thereon.

FIG. 4 is a view similar to FIG. 1 of a modified form.

FIG. 5 is a vertical sectional view substantially along the line 5—5 of FIG. 4.

FIG. 6 is a fragmentary elevational view of the mold configuration of FIG. 4.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring first to FIGS. 1–3 inclusive, the mold construction is adapted for casting single crystal turbine blades and vanes as described by way of example in the Piearcey U.S. Pat. No. 3,494,709. These articles are preferably cast from many of the well-known high-temperature alloys as described in this patent or in the VerSnyder U.S. Pat. No. 3,260,505.

The mold to be described is formed by the well-known shell molding process in which thin mold shells are formed around disposable patterns as for example wax patterns. The apparatus shows the mold shells after the wax has been melted out in order that the cavities in which the alloy is cast may be more readily distinguished. It will be understood however that after the mold material has been completely formed around the patterns they are melted out to leave the cavities shown and the wax pattern did, in fact, occupy all of the shown cavities prior to the baking of the mold to harden it and to provide removal of the wax.

The article mold **2** has a centrally located airfoil cavity **4** extending from a root portion **6** to a shroud portion **8**. Above the shroud is the filling passage **10** and below the root **6** is the helix **12** that selects a single crystal from the columnar growth base portion **14**. The function of the growth portion **14** and helix **12** in selecting a single crystal has been described in the co-pending application of Copley et al., Ser. No. 806,978 filed Mar. 13, 1969 and having the same assignee as the present application.

A plurality of these article molds are positioned in a ring with the chordwise dimension of the airfoil portion of the several article molds extending in a generally circumferential direction as shown in FIG. **1**. The several article molds are connected together in the circumferentially arranged relation by a disk-like filler portion **16** for the several article molds. This portion **16** has a chamber **18** therein communicating with all of the several article molds.

Between adjacent article molds is a chamber **20** defined between inner and outer mold rings **22** and **24** which are in engagement with the surfaces of the article molds as shown in FIG. **1** leaving the trailing edge and leading edge portions of the mold exposed to the adjacent chambers **20**. The chambers **20** are connected by passages **26** at the top communicating with the horizontal filling chamber **18** and the same chambers communicate at the bottom by mold extension defining a passage **28** from the chambers **20** to the chill plate **30** on which the entire mold assemblage rests. At the top of the filler portion **16** is a funnel-shaped pouring spout **32**.

As above stated, the article mold **2** with the appendages thereon is formed by dip coating a wax or otherwise disposable pattern that is the shape of the article together with the growth portion at the bottom and the filling opening at the top. When the article mold is completed the several article molds are connected to a wax pattern that is the shape of the chamber **18**. Wax is positioned between the leading edge of one article mold and the trailing edge of the adjacent mold in the shape of the chamber **20** and wax rods are positioned at opposite ends which are the shape of the passages **26** and **28**. With all of the wax in position, the entire assemblage is again dip coated thereby forming the inner and outer walls **22** and **24** together with the mold **16** surrounding the chamber **18** and the portions of the mold connecting the mold portion **16** to the individual article molds and also the portions of the mold extending down from the portion **16** to the top of the annular mold portions **22** and **24**. Once the entire mold is created as shown, the assemblage is positioned in a suitable baking oven to harden the entire mold and to melt out the wax pattern thereby leaving a mold structure as shown in the drawings.

FIG. **3** shows an interim construction between the making of the individual article mold **2** in this figure and the finished mold. In the showing of FIG. **3** a wax pattern **34** has been positioned between adjacent article molds and wax rods **36** and **38** extend from top and bottom of the wax portion **34**. At the top the rod **36** is attached to a wax disk **40** which forms the chamber **18** in the completed mold. A wax pouring spout not shown is also attached to the top surface of the disk **40**.

Accordingly when the mold is completed ready to have alloy poured therein for the formation of the several cast articles the mold assembly consists of the circumferentially spaced apart article molds **2** positioned between inner and outer rings **22** and **24** which define between them the control chamber **20** the latter being an circumferentially extending chamber since the article molds are in contact with the inner and outer mold rings and thereby break the circumferentially defined chamber into individual compartments which enclose the trailing edge of one of the article molds and the leading of the adjacent article molds.

The entire mold assembly when it is ready to have alloy poured therein is positioned within a heating device such as an induction furnace including a cylindrical susceptor surrounded by an induction coil and the mold is heated to a temperature above the melting temperature of the alloy in readiness for pouring. With the mold assembly resting on the chill plate **30**, the alloy within the mold is in contact with the chill plate through the growth portion **14** of the article mold and through the passages **28** leading to the individual compartments of the control chamber **20**. Solidification begins at the chill plate and moves upwardly through the growth portion and through the helix where a single crystal is selected to grow into the article forming portion of the article mold. Columnar grain growth extends upwardly through the passage **28** and into the chambers **20** and it is the solidification in these chambers and the absorption of the heat from the article mold into the solidified alloy and the chambers **20** and the fence by conduction through the solidified alloy and the passage **28** to the chill plate that permits a precise control of the solidification rate and thereby the configuration of the mushy zone that is to say the liquid-solid interface of the solidifying alloy in the article molds. By suitable dimensioning of the passage **28** the rate of heat removal from the article mold may be so controlled that the liquid-solid interface remains substantially flat and horizontal during the entire solidification cycle. A larger overall heat conduction path leads to a higher thermal gradient.

Referring now to FIGS. **4**, **5** and **6** the article mold **52** is similar to that described above and has the growth zone **54** at the bottom connected by a helix **56** to the article forming portion and with an extension **58** at the top of the article forming portion which forms a passage for filling the article mold. Several of these article molds are positioned in a ring with the chordwise direction of the airfoil portion of the mold extending in a generally radially position rather than circumferentially as in FIG. **1**. Inner and outer rings **60** and **62** define between them a substantially annular chamber **64**. The inner and outer rings communicate and are in vertical engagement with the leading edges of the article mold by outward and inwardly projecting ribs **66** and **68** formed on the inner and outer mold rings respectively. As in the apparatus above described, there is a horizontal mold portion **70** at the top of the mold assembly and this has a horizontal chamber **72** communicating with all of the article molds and also through vertical passages **74** in the mold communicating with the compartments of the annular chamber **64** which are located between adjacent article molds. The mold also has vertical passages **76** extending downwardly from the segments of the annular chamber **64** to engage at their bottom ends with the chill plate **78** as do the growth zones **54** of the article mold.

The mold assemblage is made in the same manner as above described with respect to FIGS. **1**, **2** and **3**. A wax pattern for example is formed in the configuration of the article desired with a helical projection at the bottom and a configuration corresponding to that of the chamber in the growth zone portion of the article mold. The wax pattern has at the top an extension that serves to form the passage through the upward extension **58** on the article mold and from there upwardly to communicate with a horizontal wax disk the shape of and serving to form the chamber **72** when the second step of making the mold is performed. When the wax pattern for the article mold is completed it is dipped into appropriate mold forming slurries by the usual technique of making the shell mold thereby forming the article mold **52** with the extensions at top and bottom as shown. This article mold is then assembled together with the was pattern to form the chamber **72**, wax patterns forming passages **74** and **76** and a ring of wax that forms the annular chamber **64** and encloses the article molds from top to bottom of the portion of the article mold that becomes the finished cast article that is being cast for use. Suitable grooves are formed in this wax pattern to communicate with the leading and trailing edges of the article mold thereby permitting the mold forming material to contact the first shell when the assemblage is dipped to form the secondary mold coating.

FIG. **6** shows the assemblage of the article molds together with the surrounding and associated wax patterns by which the secondary mold is produced. As shown in this figure, the pattern assembly includes the flat disk **80** having the wax rod **82** extending downwardly into the article mold and the parallel wax rod **84** extending downwardly to communicate with the heavy wax ring **86** that surrounds and embeds the individual article mold for the effective portion of the article mold. The assemblage also has the downwardly extending wax rods **88** from the wax ring **86** down to a level coincident with the bottoms of the growth portions **54**. Grooves **90** are formed in the wax and extend inwardly from the outer and inner vertical surfaces of the wax to expose the leading and trailing edges of the airfoil portion of the article mold **52**. It is these grooves that permit the formation of the connecting ribs **66** and **68**.

The assemblage of FIG. **6** is then coated with mold material as by the usual shell molding process thereby forming the secondary mold which surrounds the wax pattern and assemblage of FIG. **6**. This secondary mold having been completed the device is placed in a furnace where the mold is baked to harden the material thereof to melt out the wax pattern leaving the empty casting spaces as shown in FIGS. **4** and **5**.

Once the mold is hardened ready for use, it is positioned within a suitable heating means preferably an induction furnace and preferably all enclosed within a vacuum and the mold is heated to a temperature above the melting point of the alloy. The molten alloy is then poured to fill the spaces within the mold and solidification begins where the alloy contacts the chill plate in the same manner as above described with respect to FIGS. **1**, **2** and **3**.

With respect to both modifications of mold apparatus described, once the alloy is entirely solidified and cooled so that the mold with the alloy therein can be handled the outer or secondary mold is removed to as great an extent as possible and the molded parts of the casting are pulled apart. Because of the particular construction of the mold apparatus in both cases such that the segments of the control ring of alloy, that is to say the alloy that is formed within the segments of the annular chamber **20** of FIG. **1** or the segments of the annular chamber **64**, are separable one from another, the cast segments may be readily withdrawn from one another thereby disengaging the cast control alloy from the article mold and the cast article within the mold. Subsequently, with the removal of the helix of cast alloy at the bottom of the article mold and with the removal of the cast article from the portion of solidified alloy extending upwardly from the top of the article portion the latter is in readiness for inspection and for machining for use.

With the use of the alloy in the annular chambers **20** or **64** and the effective control of the solidification rate as well as the temperature of the article mold during solidification of the alloy it is possible to obtain acceptable cast articles all of a single crystal and free of the equiaxed grains that tend to form on the surface when appropriate temperature controls are not provided. Although the article produced by a casting technique of this type appears to be a relatively small portion of the total amount of alloy used in making the casting it will be readily understood that the remainder of the cast alloy, the so-called revert, may be added to the alloy for the subsequent casting operations and is not in any sense wasted.

We claim

1. A mold assembly for casting a plurality of single crystal articles at one time including,

a plurality of article molds each having a crystalline growth portion at one end thereof, said growth portion having an open bottom end to engage a chill plate,

inner and outer mold rings defining an annular chamber in which the article molds are positioned, with said article molds in contact with both rings to form individual compartments in the chamber between adjacent article molds,

a mold extension on said rings between adjacent article molds and at the end adjacent said growth portion defining in said extension several passages one extending downwardly from each compartment and each having an open bottom end to engage said chill plate, each said passage being smaller in cross sectional area than the compartment thereabove to control the amount of heat transmitted to the chill plate,

a filling connection at the other end of each of the article molds for filling each of said molds, and filling extensions projecting upwardly from said inner and outer mold rings forming passages through which the compartments in the annular chamber may be filled.

2. A mold assembly as in claim **1** with the article molds are in contact with said mold rings for a part of the outer surface area of the article molds thereby to define individual casting cavities in said annular chamber between adjacent molds.

3. A mold assembly as in claim **1** in which the article molds are spaced apart circumferentially and are in contact with and supported by the rings thereby dividing the annular chamber into individual casting cavities between adjacent molds.

4. A mold assembly as in claim **1** in which the article molds are constructed to produce a blade shape having an airfoil configuration for part of the length and the chordwise direction of the airfoil portion extends circumferentially of the annular chamber.

5. A mold assembly as in claim **1** in which the article molds are constructed to produce a blade shape having an airfoil configuration for part of the length and the chord of the air-foil portion extends crosswise of the annular chamber.

6. A mold assembly as in claim **5** in which the ends of the airfoil portion of the mold are connected to the mold rings.

7. A mold assembly as in claim **4** in which the ends of the airfoil portion of the mold are positioned in adjacent casting cavities.

8. A mold assembly for casting directionally solidified articles, said assembly being mounted on a chill plate for the casting operation, said assembly including,

article forming molds each having a grain growth portion at the bottom thereof,

inner and outer mold walls defining an annular chamber within which said article forming molds are positioned with said molds in engagement with said inner and outer mold walls over only a portion of the area of the article mold walls and defining compartments in said chamber between adjacent article molds, said inner and outer mold walls having extensions thereon at the bottom thereof for each compartment, each extension forming a passage therein, said growth portions and said extensions both being open at the bottom end thereof to engage the chill plate, and

common means for filling said article forming molds and said compartments, the area of said passages controlling the rate of heat loss from the material in the compartments to the chill plate.

9. A mold construction for producing single crystal articles comprising:

a first ring,

a second ring positioned within and spaced from the first ring, the first and second rings being positioned to form an annular mold cavity therebetween;

a chill plate, the first and second rings being positioned thereon with the cavity open at the top to receive molten metal and with mold extensions at the bottom of the annular cavity forming a plurality of passages terminating in heat transfer relationship with the chill plate, and

a plurality of smaller article molds positioned within the annular mold cavity and in contact with said rings to form individual compartments between adjacent article molds, with one of said passages communicating with each of said compartments, each article mold having a crystal selecting passage at the lower end thereof constructed to permit the entrance into each of said article molds of a single grain of metal, and a growth zone between said passage and the chill plate the crystal selecting passage being a restriction to heat flow from the interior of the article molds to the chill plate, heat from within the article molds being transferred laterally into the metal the compartments in the annular chamber and vertically to the chill plate through said first mentioned passages thereby controlling the configuration of the liquid-solid interface within the article molds and the annular chamber with respect to the chill plate the area of the first mentioned passages controlling the rate of heat conduction from the compartments to the chill plate.

10. A mold construction as in claim **9** wherein,

the lower end of the crystal selecting passage on each article mold is spaced above the chill plate, and

each article mold is in contact with and supported by said first and second rings.

11. A mold construction as in claim **10** wherein,

the lower end of the crystal selecting passage is at least one inch above the chill plate.

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