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Tschinkel et al.

[11] **3,763,926**

[45] **Oct. 9, 1973**

[54] **APPARATUS FOR CASTING OF DIRECTIONALLY SOLIDIFIED ARTICLES**

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[52] **U.S. Cl.** **164/338**, 164/60, 164/126, 164/136, 164/348

[51] **Int. Cl.** **B22d 27/04**, B22d 25/06

[58] **Field of Search** 164/60, 126, 128, 164/136, 348

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[57] **ABSTRACT**

Apparatus for casting directionally solidified articles either columnar grained or single crystal in which the rate of solidification is controlled by gradual immersion or submergence by a liquid coolant.

13 Claims, 8 Drawing Figures

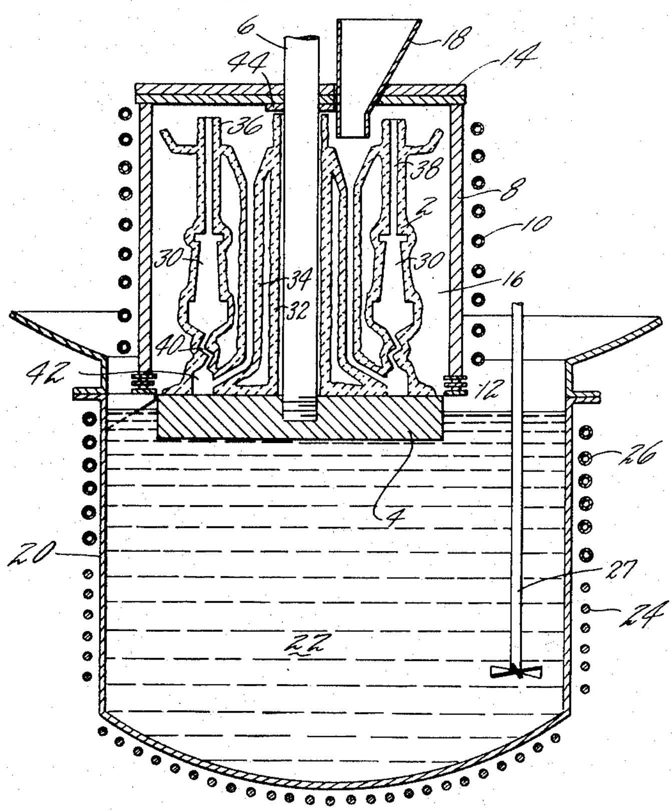

FIG. 1

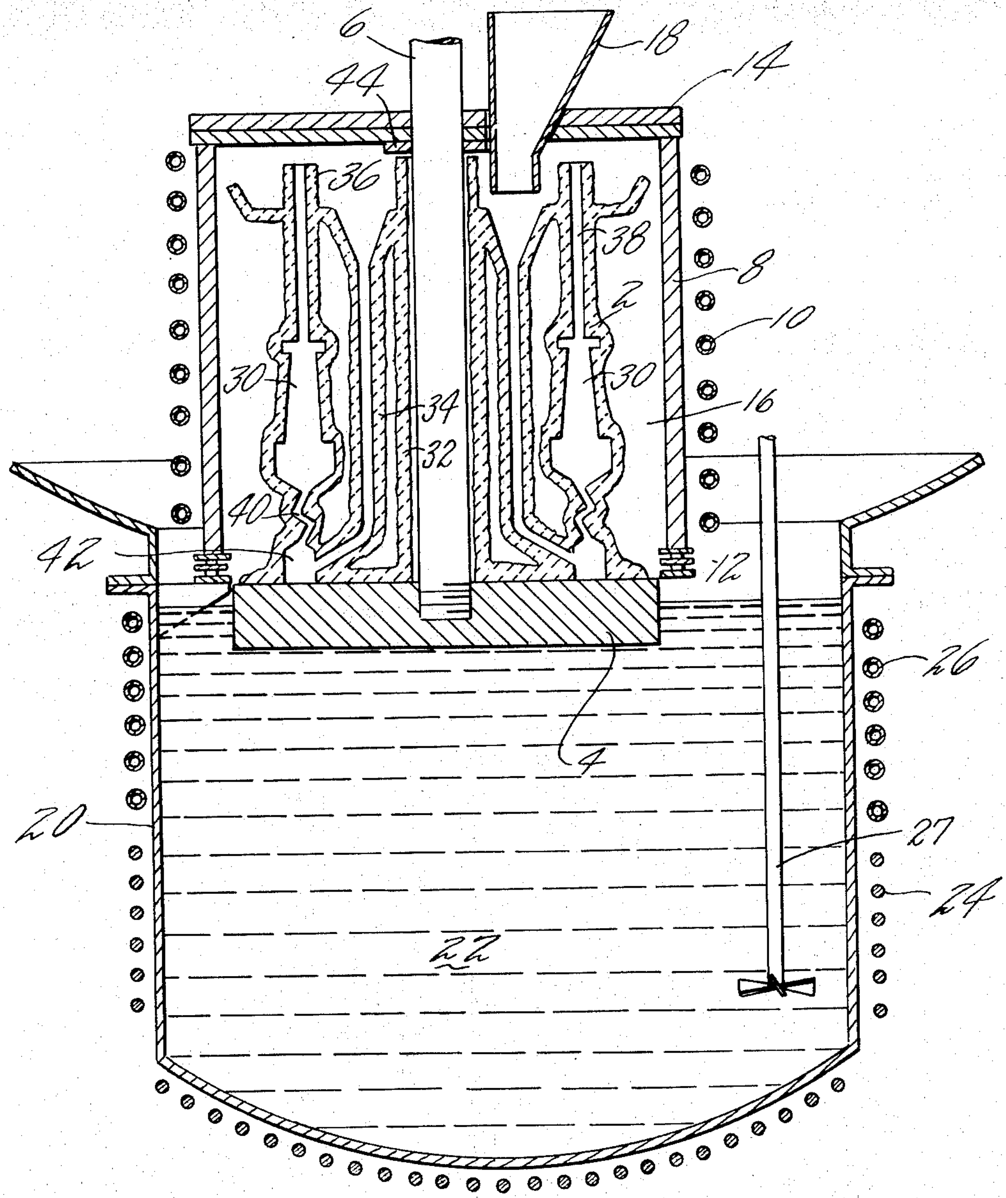

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FIG. 2

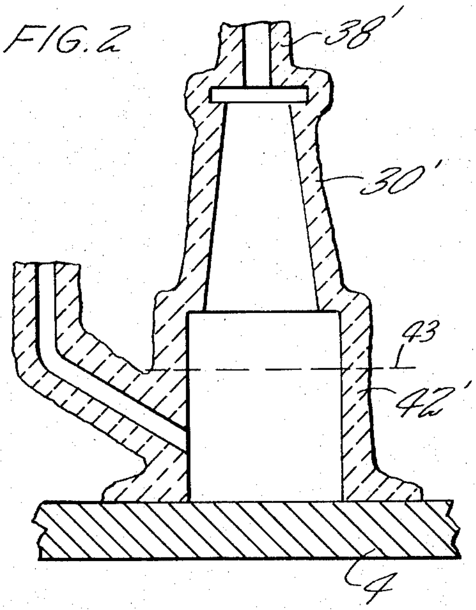


FIG. 3

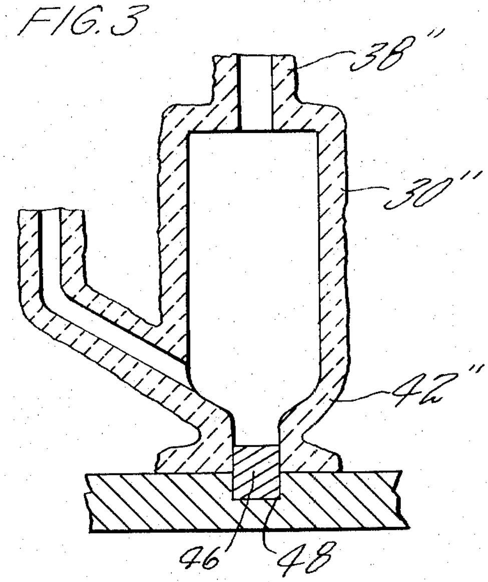


FIG. 4

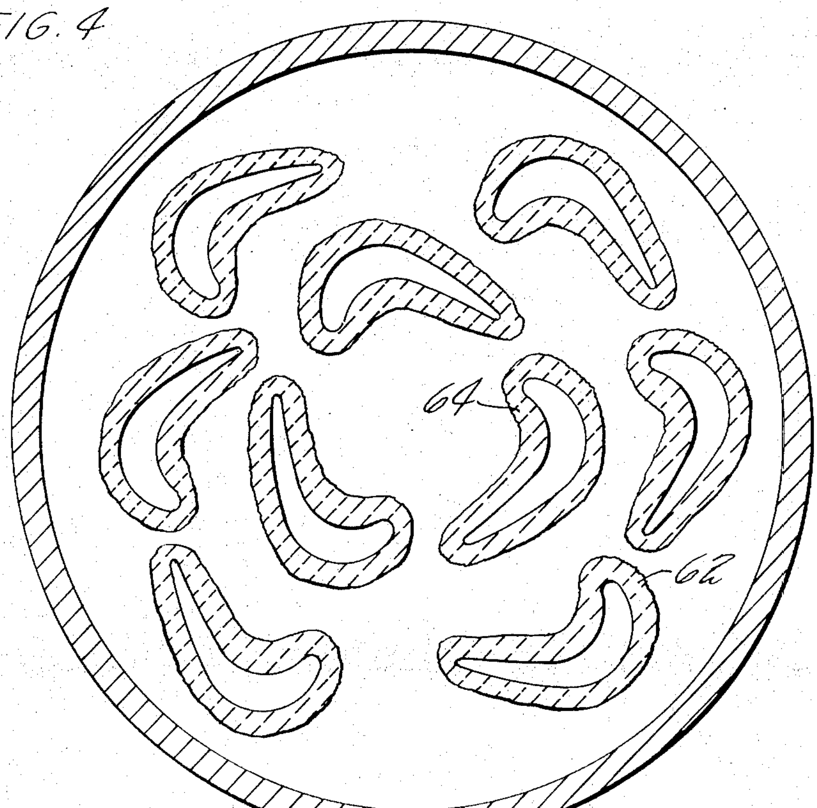
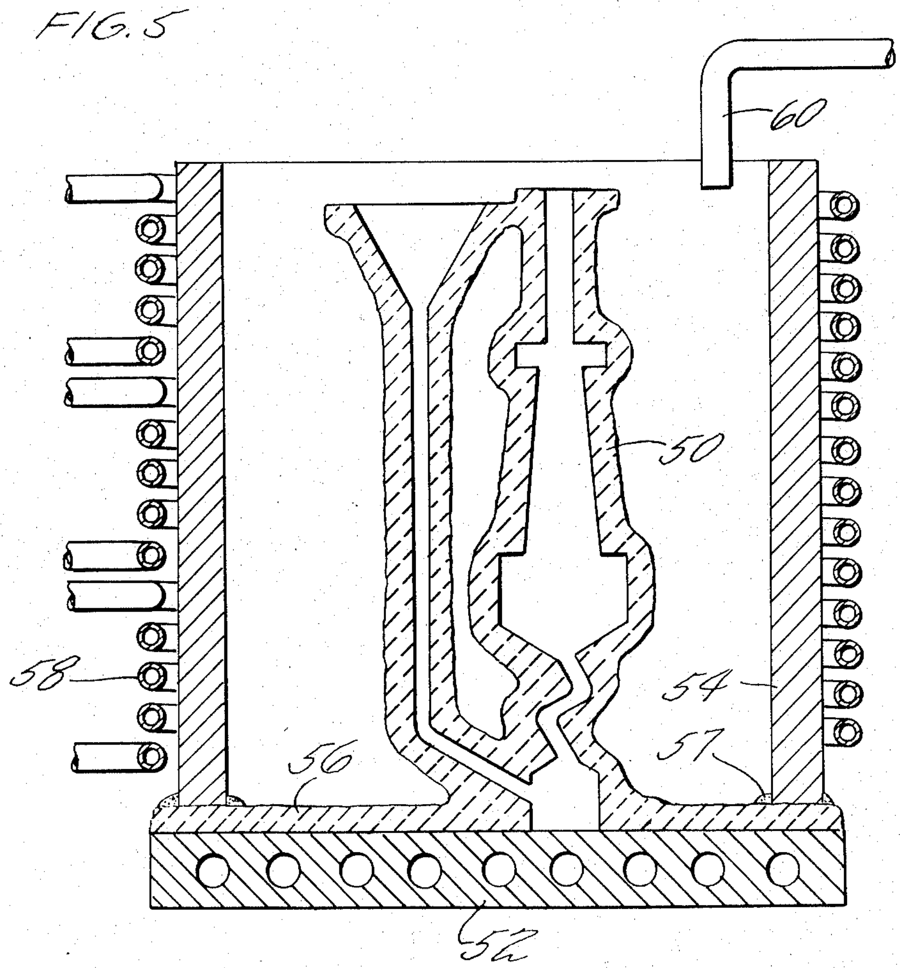


FIG. 5



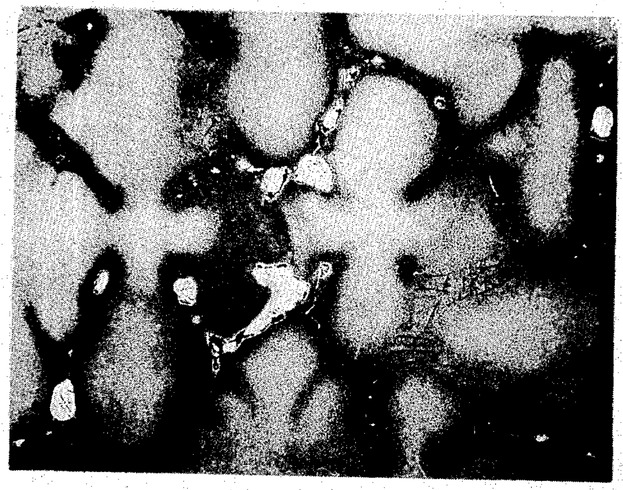


FIG. 6

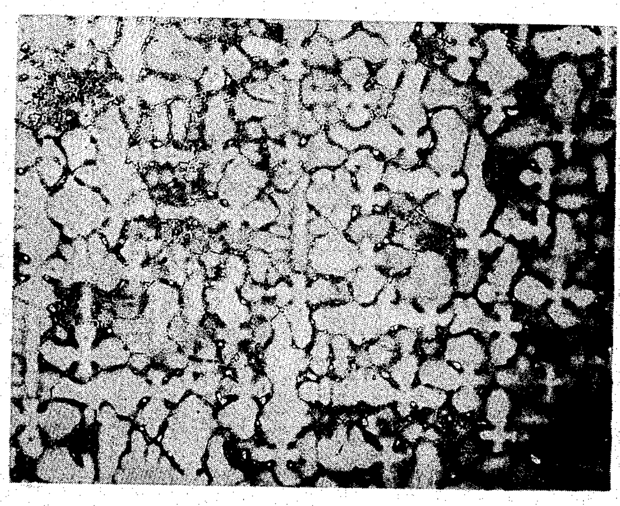


FIG. 7

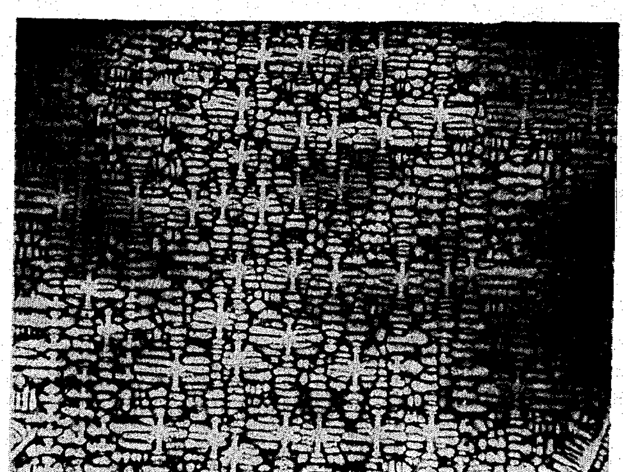


FIG. 8

APPARATUS FOR CASTING OF DIRECTIONALLY SOLIDIFIED ARTICLES

BACKGROUND OF THE INVENTION

One concept of high rate solidification of directionally solidified cast articles is described in the copending application of Barrow, et al., Ser. No. 63,143 filed Aug. 12, 1970, having the same assignee as this application. The apparatus and process of that application produced a much higher rate of directional solidification than was previously possible by gradual withdrawal of the mold from the heating chamber and by simultaneously exposing the mold during the solidification process to the cooler surrounding walls of the apparatus. In this way in addition to the downward conduction of heat through the solidified alloy to the chill plate, a substantial heat removal was accomplished by radiation from the walls of the mold below the liquid-solid interface. Since a fine dendritic spacing is desirable and since the dendritic spacing decreases with increasing rates of solidification of the alloy (the growth rate), it is desirable to provide for more effective cooling of the mold during the solidification process.

The dendrites formed within the single crystal or the columnar grains in the cast article are distinguished from the surrounding material by differences in concentration of some constituents. Embedded carbide particles and eutectic microconstituents, for example, tend to accumulate in the normally weaker interdendritic regions and the strength of the alloy is decreased by such inhomogeneities. The size of the embedded particles and pools of microconstituents is significantly reduced by a reduction in dendritic spacing in the casting since the interdendritic spaces are smaller with closer dendritic spacing. After the casting is completed, it is desirable to homogenize the cast alloys by heating them at a temperature close to the solidus temperature. Since diffusion in solids is a slow process, this homogenization of the alloy may require hundreds of hours where the dendritic spacing is relatively large so that normally complete homogenization of the dendritic structure is not practical. The diffusion time for complete homogenization at a given temperature is proportional to the square of the distance between the dendrites so that a reduction in dendritic spacing by a factor of 10 can reduce the annealing time by a factor of 100 thereby bringing the required time for complete diffusion down to a few hours. In this way the homogenization treatment would become a practical procedure. The spacing of the dendrites is significantly reduced by more rapid solidification of the material being cast.

STATEMENT OF THE INVENTION

One of the principal features of the present invention is the very rapid heat removal from the mold in conjunction with a sharp transition between the hot and cold surroundings in order to maintain a high thermal gradient and also a high growth rate for making the cast article. Another feature is the use of a liquid coolant into which the mold is immersed or in which the mold is submerged gradually for the rapid extraction of heat from the mold, thereby obtaining the desired grain growth within the mold. Another feature is the use of this liquid coolant to circulate around all of the several molds in a multiple mold casting so that the heat removal from the several molds will be the same and, accordingly, the desired grain growth will be obtained within all of the molds. A particular feature of the invention is the control of the dendritic growth within the casting in such a way as to significantly reduce the distance between the dendrites and thereby minimize the segregation of the microconstituents in the interdendritic regions.

In the use of this apparatus for making directionally solidified castings, the apparatus is particularly adapted for making columnar grained articles as described in VerSnyder U.S. Pat. No. 3,260,505 or the single crystal articles of Piearcey U.S. Pat. No. 3,494,709. These latter are a particular form of columnar grained articles being only a single grain, rather than the plurality of parallel grains as in VerSnyder. The apparatus is also particularly usable on the alloys of Gell U.S. Pat. No. 3,567,526, which also describes a form of columnar growth. Thus, the term "columnar growth" is intended to encompass all of these several types of grain growth.

According to the invention, the apparatus includes a heating chamber within which the mold is positioned for raising the mold to a high temperature above the melting temperature of the material to be cast, a container for a liquid bath below the heating chamber and in which the mold is immersed or submerged, a device for filling the mold, and a device for moving the mold relative to the chamber and container for gradually immersing the filled mold into the cooling liquid and simultaneously withdrawing it from the heating chamber. The process is carried out by heating the mold before filling to a temperature above the melting temperature of the material to be cast, pouring the molten material into the mold and then gradually withdrawing the mold from the heating area and simultaneously submerging it gradually into a liquid cooling bath thereby establishing a steep thermal gradient in the material in the mold and causing a vertical solidification of the material in the mold from the base of the mold to the top at a controlled rate.

A modified form of the invention provides for gradually reducing the heat supplied to the mold from bottom to top and gradually filling the container with a liquid coolant. In either form of the invention, the filled mold is gradually surrounded with a cooling liquid from bottom to top of the mold and at the same time, the heat supplied to the mold is gradually reduced from bottom to top by withdrawal of the mold or by a step-by-step reduction in the heat input to the mold as the level of the cooling bath effectively moves upwardly around the mold.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a vertical sectional view through an apparatus embodying the invention.

FIG. 2 is a fragmentary vertical sectional view of a modification.

FIG. 3 is a fragmentary vertical view of another modification.

FIG. 4 is a transverse sectional view through a multiple mold showing the effectiveness of liquid cooling.

FIG. 5 is a vertical sectional view through a modified form of apparatus.

FIG. 6 is a transverse microstructure of a single crystal cast conventionally.

FIG. 7 is a similar view at the same magnification of a single crystal cast by the process of the present application.

FIG. 8 is a similar view at the same magnification of a single crystal cast by the present process but at a faster cooling rate.

PREFERRED EMBODIMENT OF THE INVENTION

Referring first to FIG. 1 which shows the apparatus of the present invention, the article to be cast is made in a mold 2 which rests on a support or chill plate 4, the latter being carried by a suspending shaft 6 attached as by a threaded connection 7 to the plate. In the position of the mold shown, it is surrounded by a susceptor 8 in the form of a graphite sleeve which in turn is surrounded by induction heating coils 10 by which the susceptor may be heated with the latter in turn heating the mold prior to the mold filling operation. Suitable heat shields 12 are positioned at the lower end of the susceptor sleeve 8 near the periphery of the chill plate and other heat shields 14 close the upper end of the chamber 16 formed within the susceptor 8 and within which the mold is positioned. These heat shields 14 are in the form of a removable cover. A pouring cup 18 may be positioned in the shield 14 at the top of the chamber.

Positioned below the heating chamber 16 is a tank 20 which holds a liquid 22. The tank 20 may have heating elements 24 surrounding it for raising the temperature of the bath to the desired temperature for immersion of the mold therein and the chamber is also preferably surrounded by cooling coils 26 adjacent the upper end of the tank for the purpose of maintaining the desired temperature within the bath of liquid especially as the mold is immersed therein during the solidification process. Suitable stirring means 27 may be provided to assure a circulation of the liquid bath when the casting process is being carried out. The tank may be secured to the wall of the vacuum chamber not shown in which the apparatus is positioned.

The position of the heating and cooling coils 24 and 26 around the tank serves to create and strengthen convective currents in the liquid bath to circulate the liquid and thereby maintain a more nearly constant temperature for the portion of the bath in which the mold is being immersed. The effect of the immersion of the mold is to heat the surrounding liquid rapidly causing an upward flow toward the surface. The cooling coils, near the top of the liquid bath, serve to cool the adjacent liquid and cause a downward flow along the inner surface of the tank toward the bottom. At this point the liquid is again heated by the heating coils and an upward flow near the middle of the tank is caused. Thus, in some instances, the circulation of the liquid bath by the stirring device may be omitted. It will be understood that the drawing shows the several parts merely diagrammatically and suitable support means are provided for maintaining the tank 20 in a predetermined relationship with the heating chamber thereabove. The level of the liquid bath 22 is preferably such that it partially submerges the support plate 4 therein when the mold is within the heating chamber for the heating and pouring operation and in this way this plate serves as an effective chill plate without the need for a circulation of coolant through the plate.

The mold is preferably of the well known ceramic shell mold type and as shown is a multiple mold and has two article forming portions 30 positioned on opposite sides of a central carrying cylinder 32. The article portions 30 are shown with a cavity in the shape of a turbine blade by way of example. The cylinder 32 is of a dimension to fit around the vertical shaft 6 as shown. Between each of the article portions of the mold and the central sleeve 32 are vertically filling tubes 34 communicating at their top ends with a filling ring 36, the latter at one point being positioned directly below the pouring cup 18. Each article portion of the mold has an upward projecting riser portion 38 terminating at a point at least as high as the top of the filling ring 36. Below and communicating with the article forming portion of the mold is a growth zone including a crystal selector 40 which may be a helix defining therein a helical passage for selecting a single crystal to grow into the article portions. The helical passage terminates at the bottom in the main growth zone 42 in which columnar grains are grown. The filling tubes 34 communicate with the growth zone 42 as shown. Thus, when alloy is poured into the cup 18, it flows into the ring 36 through the tubes 34 into the growth zone and thence upwardly through the crystal selector to fill the article portion of the mold and upwardly into the riser. This mold arrangement is suitable for making single crystal articles.

Referring now to FIG. 2, a portion of a mold is shown which is adapted for making columnar grained cast article instead of single crystal articles. To do this, the article mold 30′ has the riser 38′ at the top and a growth zone 42′ at the bottom open to the chill plate. The crystal selector of FIG. 1 is omitted and the growth zone communicates directly with the bottom end of the article mold portion, the dividing line being represented by the dashed line 43, FIG. 2, and it is along this line that the growth portion of the casting would be severed from the article itself.

Crystalline structures of other orientations than 001 9 may be made by the use of a mold as shown in FIG. 3. In this arrangement, the article mold portion 30″ has the riser 38″ at the top, and a growth zone 42″ at the bottom. This growth zone receives a single crystal slug 46 of the desired orientation and the base of this slug is preferably set into a recess 48 in the support plate 4 so that this slug will not be totally melted during heating of the mold. When the alloy is poured, single crystal growth occurs with the dendritic orientation throughout the arrticle the same as that of the slug 46. In FIG. 1 the crystal selector is considered a part of the growth zone when making single crystal castings.

One particularly suitable liquid for use in the cooling process is tin because of its low vapor pressure and because of its low melting temperature (450° F). A suitable temperature for the tin bath is about 500° F since clearly the lower the temperature of the bath the faster the cooling rate will be. As above stated, the plate 4 is partially immersed in the tin bath at the start of the casting operation and serves as a chill plate.

The process is desirably carried out in a vacuum or in an inert atmosphere and to this end the apparatus is positioned within a vacuum chamber. With the apparatus in the position of FIG. 1 and with the mold in position resting on and sutiably secured to the support plate to prevent leakage of molten material from within the mold, the latter is heated by energizing the induction coils 10 to raise the temperature of the mold itself at least to the melting temperature of the alloy and preferably to a temperature as much as about 300° F above the melting temperature. Where the article to be cast is a turbine blade which is the shape shown for the article portion of the mold in FIGS. 1 and 2 of the drawings, one superalloy suitable for the purpose is Mar-M

200 although many other alloys are equally suitable as described, for example, in the patents to VerSnyder U.S. Pat. No. 3,260,505 and Piearcey U.S. Pat. No. 3,494,709 and also in the patent to Gell, et al. U.S. Pat. No. 3,567,526.

The alloy to be cast is heated to a point about 300° F above the normal melting point of the alloy so that it has a significant superheat. With the mold above the melting point of the alloy and with the alloy itself superheated to this extent, the alloy is poured into the mold, filling the mold at least to a point above the article portion of the mold and preferably substantially to the level of the pouring ring **36.** Since the temperature of the support plate **4** is kept substantially at the temperature of the liquid bath, dendritic growth immediately begins within the growth zone **42** of the mold and as solidification continues upwardly through the growth zone, the grain growth becomes columnar as described in the Piearcey patent. Almost immediately after the alloy is poured and when grain growth has begun, the support plate with the mold thereon is gradually lowered from the heating chamber **16** so that the support plate is completely immersed and then the mold is gradually immersed within the liquid cooling bath. As the mold moves downward into the bath, the liquid coolant flows over the surface of the support plate and around the various portions of the mold. Since the coolant is in contact with all the outer surfaces of the mold, it completely surrounds the mold and rapidly removes heat from all portions of the mold thereby increasing the rate of solidification of the alloy in a vertical direction. The grain selector **40** functions in much the same manner as the crystal selector in the Piearcey patent to cause the growth of a single crystal from the main growth portion into the article forming portion of the mold.

The mold is gradually and continually moved downward into the liquid bath at such a rate that the level of the cooling bath does not precede the solidus level by any substantial amount so that the removal of heat from the mushy zone of the solidifying alloy is vertically downward and the level of the liquid-solid interface will remain substantially horizontal. This will assure the growth of a single crystal within the article portion of the mold and prevent nucleation of spurious grains along the surfaces of the mold. The high resultant thermal gradient and the level interfaces also tend to suppress convection due to concentration differences in the molten superalloy which could otherwise lead to a solidification defect known as freckles.

In using a superalloy for making turbine blades, if the blade is 4 inches in length, for example, and the height of the growth zone **42** is preferably at least an inch, the total height of the mold including the riser would be 8 inches. In a specific casting operation in making a single crystal blade, this mold is heated to 2,850° F except for the portion closely adjacent to the support plate. The alloy is heated to 2,850° F and is then poured into the mold which is at this time positioned on the support plate **4** and within the heating chamber. The support plate and the mold thereon are held in the position shown for 1 to 5 minutes for the start of the columnar growth in the growth zone before a downward vertical movement of the chill and mold into the liquid tin at 500° F is started. The downward movement of the chill and mold is carried out at a uniform rate of 120 inches per hour until the mold is immersed to a point at least 1 inch above the top of the article portion of the mold thereby assuring a growth of a single crystal through the entire article forming portion of the mold.

Since the distance that the mold must move downward to be immersed to this extent within the liquid tin bath is 6 inches, it will be apparent that the complete operation for adequate immersion of the mold requires only 3 minutes plus the holding time from the time of pouring the mold for a completion of the solidification process. The mold is then withdrawn upward and the device is preferably so constituted that the mold is drawn up through the heating chamber to a point thereabove, the heat shields **14** being carried upward therewith by a support collar **44** on the shaft. With the mold and support plate completely above the apparatus shown, removal of the mold from its position on the support plate is done by unscrewing the plate and retracting the mold from its position around the shaft. Any suitable mechanism not a part of this invention may be provided for this purpose. Obviously, the suspension shaft could be moved laterally to position the mold and plate over a suitable bench rather than over the hot chamber **16.**

The heating coils are continuously energized and, therefore, the susceptor **8** is retained at its high heat during the downward movement of the mold into the cooling bath so that, above the level of the bottom of the susceptor, the mold is still kept near the 2,850° F temperature. In this way a very high thermal gradient is maintained in the material within the mold between the level of the bottom of the susceptor and the top of the tin bath. That is to say, the mold is surrounded by a temperature above the melting point of the alloy throughout the entire height of the susceptor and the lower portion of the mold is immersed in a cooling bath at 500° F at a very short distance below the bottom end of the susceptor thereby establishing this very high thermal gradient. The steepness of the thermal gradient at the interface is determined to a great extent by the spacing of the susceptor above the surface of the bath, by the temperature and effectiveness of the bath, and by the alloy superheat.

Further, the rate of the upward movement of the liquid-solid interface, the growth rate, is determined by the rate of downward movement of the mold into the liquid bath. Since the bath is in contact with the outer surfaces of the mold, the rate of heat withdrawal from the mold and thus from the alloy at and below the surface of the liquid bath by conduction will be extremely rapid. It is desirable to have a relatively thin mold wall thereby to improve the heat transfer rate and thus the wall thickness of the mold will be limited by the strength needed to withstand the pressure of the material within the mold during the casting process.

Instead of withdrawing the mold from the heating chamber and immersing it in a liquid coolant bath, the mold may be submerged gradually by pouring the cooling liquid into a chamber surrounding the mold. As shown in FIG. **5**, the mold **50**, which is shown as a single article mold, rests on a chill plate **52** and is surrounded by a susceptor **54.** The foot **56** of the mold is extended to overlie the entire chill plate and to extend under the susceptor at the periphery of the chill plate. The susceptor is held to the mold foot by cement **57** to form a liquid tight connection at this point. The susceptor is surrounded by an induction heater **58** which consists of several axially aligned coils so that the energy supplied to the coils may be gradually reduced from the bottom to the top of the susceptor. A pipe **60** provides for admission of a supply of liquid coolant into the chamber surrounding the mold. In use, the mold having been heated to the desired temperature as above described, is filled with the superheated molten alloy and solidification is started at the chill plate by the supply of coolant to the passages in the chill plate. After a short period for the columnar growth to be established in the mold at the chill plate, a cooling liquid is supplied to the chamber and simultaneously the lowermost heating coil is turned off. The coolant surrounds the mold and rapidly extracts heat from the mold and the alloy therein to cause upward solidification of the alloy. The rise of coolant in the chamber for submerging the mold is at the same rates given above for the downward movement of the mold in FIG. **1.** Except for the need for the tin to absorb heat from the susceptor, the effect is the same in the submergence of the mold by the poured-in coolant as in the immersion technique of FIG. **1.** As the level of the coolant rises within the chamber, successive coils are shut down so that only the portion of the susceptor above the level of the coolant continues to be heated.

Although the above process has been described with respect to superalloys having a nickel or cobalt base, it should be understood that the apparatus and process are applicable not only to the casting of this particular type of alloy but may be equally well adapted for the casting of other materials, for example, some of the eutectic type of alloys among which may be the materials described in Lemkey U.S. Pat. No. 3,552,953 and Thompson U.S. Pat. No. 3,554,817. Accordingly, the use of the term alloy is intended not to be limited strictly to known superalloys of the nickel or cobalt base as in the above VerSnyder and Piearcey patents but is more generally intended to mean any mixture of materials subject to being directionally solidified preferably in a columnar grained or single crystal configuration.

In the solidification of these eutectic-type alloys, two conditions in general are highly desirable. First, maintaining at the liquid-solid interface a large ratio of thermal gradient to growth rate and, second, maintaining a flat and horizontal liquid-solid interface since these eutectic-type alloys can tolerate only a very small change from this orientation. This process offers the very high thermal gradient desired and allows the maximum permissible growth rate which is higher with higher thermal gradients. Since the thermal gradient is several times as high as by other known techniques, the growth rate may also be several times as high without affecting the ratio of thermal gradient to growth rate.

The rate of solidification is limited by the rate of removal of heat from the alloy which produces no excessive curvature of the solidus surface. Since the size of the dendrites grown is a function of the rate of cooling, the shorter the time for solidification, the closer will be the dendritic structure. In experimentation, growth rates as high as 180 inches per hour have been realized and such rates or higher are not unreasonable in casting, for example, blades and vanes for gas turbine engines. The growth rate depends on the cross-sectional area of the material in the mold and also the shape of the article since, for example, a blade shape has a greater surface area than a circle for the same cross-sectional area and will therefore lose heat faster.

As above stated, the thermal gradient is controlled by several parameters such as the amount of superheat in the molten alloy at the time of pour, the temperature of the liquid bath and the spacing between the bottom of the heating chamber and the surface of the liquid bath. The thermal gradient may be quite steep and gradients as high as 500° F per inch have been obtained. Thermal gradients as high as 1,000° F per inch are feasible with the present invention.

The growth rate, the rate at which the solidification front moves upward, is controlled essentially by the rate at which heat can be removed from the mold. With the thin mold wall, the heat removal is a function of the cross-sectional area of the alloy compared to the surface area, the rate at which the mold is immersed in the bath and the ability of the bath to accept the heat removal without a significant increase in temperature. This last parameter is thus affected by the volume of the bath, the specific heat of the material of the bath, the circulation of the bath to keep the liquid close to the mold in motion and the external cooling means for temperature maintenance. The growth rate is thus substantially independent of the thermal gradient and either may be adjusted independently for optimum results.

The effects of the high solidification rate and the high thermal gradient of this invention is emphasized in FIGS. **6, 7,** and **8.** FIG. **6** is a transverse microstructure of a single grain at 100 magnification of Mar-M 200 alloy cast by directional solidification techniques as in the VerSnyder patent. This shows the large dendrites with comparable large dendrite spacing, the white areas being eutectic microconstituents forming areas of inhomogeneity that decrease the strength of the alloys. FIG. **7** shows a similar microstructure of the same alloy cast by the present techniques at 25 inches per hour immersion rate with obviously a much finer dendrite structure and closer interdendrite spacing and smaller embedded carbide particles and eutectic microconstituents. The alloy is thus inherently stronger and more resistant to fatigue. The smaller dendritic structure and spacing also extends throughout the cast article and thus provides much more uniform mechanical properties such as fatigue strength, stress rupture and yield strength in all areas of the casting. This minimizes the scatter of mechanical properties characteristic of more conventionally cast articles.

FIG. **8** is a transverse microstructure also at 100 magnification of the same alloy as in FIGS. **6** and **7** but solidified by the present techniques with a 180 inches per hour immersion rate. When solidified at this rate, the dendritic structure and spacing is very much smaller than at the slower immersion rate of FIG. **7,** and the carbide particles and eutectic microconstituents are also much smaller by reason of the closer dendrite spacing. As in the casting from which the showing of FIG. **7** was made, this microstructure prevails throughout the casting, thus assuring uniform mechanical properties throughout the cast article.

The present apparatus and technique permit the reproduction of the desired microstructure and the desired mechanical properties in successive castings made so that many castings may be made, as, for example, a complete set of turbine blades or vanes for a gas turbine, all of which will have the same properties.

The pools of eutectic microconstituents shown in these microstructures may be minimized or eliminated by heating the alloy close to the solidus temperature to diffuse the materials. If the dendrite spacing is large as in FIG. 6, the cast articles must be held at this temperature for a long time since the diffusion time is proportional to the square of the distance between the dendrites. The structure of FIG. 7 can be homogenized by only a few hours of heating making such a treatment practical. The structure of FIG. 8 would require a significantly shorter time than FIG. 7 because of the smaller dendritic spacing.

This invention has utility in making a plurality of castings at one time in a multiple mold since the cooling bath will circulate within the areas between individual mold elements and allow the individual elements of the mold to cool uniformly throughout their cross section as well as along their length. FIG. 4 shows one of the advantages of the liquid bath cooling in casting a plurality of directly solidified articles at one time. This figure shows the multiple mold within a susceptor 8. Where the mold is a multiple mold having a large number of article mold portions 62 arranged in an outer ring and other article mold portions 64 in an inner ring as shown and all interconnected for filling simultaneously, the entire mold is filled at one time. With such a mold structure, the outer surfaces of the outer mold portions will lose heat rapidly by radiation to the surrounding cooler chamber wall but the inner surfaces of the outer ring of mold portions will be unable to lose heat at the same rate since the adjacent surfaces are the equally hot inner mld portions 64. Thus, the growth of the dendrite structure is irregular and the liquid-solid interface is not kept relatively horizontal but becomes tipped. This results in slower cooling and a slower than desirable rate of solidification. The inner ring of mold portions 48 are cooled even less rapidly since only small areas are exposed to any cool surface to which heat may radiate and thus the major cooling must be by conduction through the solidified alloy to the chill plate. The liquid-solid interface of these mold portions is thus also distorted from the optimum substantially horizontal configuration with resulting unsymmetrical and nonuniform dendrite growth.

The present invention, by exposing the entire periphery of each mold portion to the same cooling liquid at substantially the same temperature, makes possible the desired rapid and uniform heat removal by conduction through the mold to the cooling liquid thereby to assure a substantially uniform growth rate in all the mold portions and with the liquid-solid interface remaining substantially horizontal in all of the mold portions and at substantially the same level during the entire solidification process.

We claim:

1. Apparatus for solidification by columnar growth of an alloy including
a support plate for a mold,
a susceptor positioned above the support plate and forming a heating chamber for the mold,
means for filling the mold,
a container for a cooling liquid positioned below the susceptor,
means for supporting the plate and mold during heating and filling with the plate at least partially immersed in the cooling liquid during the heating operation, and
means for gradually surrounding the mold with the cooling liquid from the support plate upwardly around the mold for cooling the material poured into the mold.

2. Apparatus as in claim 1 in which the cooling liquid is molten tin.

3. Apparatus as in claim 1 including
liquid in the container to a level to partially immerse the support plate during heating of the mold, and
means for moving the mold and support plate gradually into the liquid in the container after the mold is filled.

4. Apparatus for directional solidification including
a support plate for supporting a mold,
a container for a liquid for cooling the mold,
a heating chamber directly above said container and having means associated therewith for heating the mold, the support plates being located at the bottom of said chamber,
liquid in the container to a height to partially immerse the support plate during heating of the mold in the chamber, and to be close to the bottom of the heating chamber, and
means for providing vertical movement between the support plate and the chamber and container for moving the mold out of the chamber and into the container thereby immersing the mold in a cooling liquid therein.

5. Apparatus as in claim 4 including
means for controlling the temperature of the liquid within the container.

6. Apparatus as in claim 5 in which the container is surrounded by heating means and also cooling means.

7. Apparatus as in claim 5 in which the means for controlling the temperature includes a cooling coil surrounding the container adjacent to portions of the surface of the pool of liquid.

8. Apparatus for directional solidification including
a support plate for a mold,
a container below and in a position to surround the support plate,
a liquid bath in said container,
a heating chamber above said container and having means associated therewith for heating the mold, the level of the surface of the liquid bath being close to the bottom of the chamber and being such that the support plate is partially immersed in the liquid while the mold is being heated within the chamber, and
means for moving the support plate vertically at a controlled rate for moving the mold out of the chamber and into the container after solidification begins on the support plate thereby immersing the mold in the liquid.

9. Apparatus as in claim 8 in which the surface of the liquid bath is closely below the bottom of the heating chamber.

10. Apparatus as in claim 8 in which the support plate is supported from above the chamber.

11. Apparatus as in claim 8 including
cooling means associated with the container and located adjacent to the level of the surface of the liquid bath for cooling the bath, and
other means also associated with the container and located adjacent to the bottom thereof for heating the bath.

12. Apparatus for directional solidification of alloys and metals including
a container for a cooling liquid,

a susceptor positioned above the container and forming a heating chamber for a mold,

means for supporting the mold within the susceptor, the bottom of the susceptor and the surface of the cooling liquid being so closely positioned that the bottom of the mold is cooled by the cooling liquid while the mold is in heating position within the susceptor,

means for filling the mold while it is in heating position, and

means for moving the mold gradually into the liquid in the container for controlled solidification of material in the mold.

13. Apparatus as in claim **12** in which means are provided for controlling the temperature of the liquid in the container.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,763,926 Dated October 9, 1973

Inventor(s) Johann G. Tschinkel et al

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 4, line 34, delete "9"

line 43, change "arrticle" to --article--

Column 8, lines 61-62 change "reproduction" to --reproducibility--

Column 9, line 30 change "mld" to --mold--

Signed and sealed this 9th day of July 1974.

(SEAL)
Attest:

McCOY M. GIBSON, JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents