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METHOD FOR CASTING HIGH TEMPERATURE ALLOYS TO ACHIEVE  
CONTROLLED GRAIN STRUCTURE AND ORIENTATION  
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Fig. 1

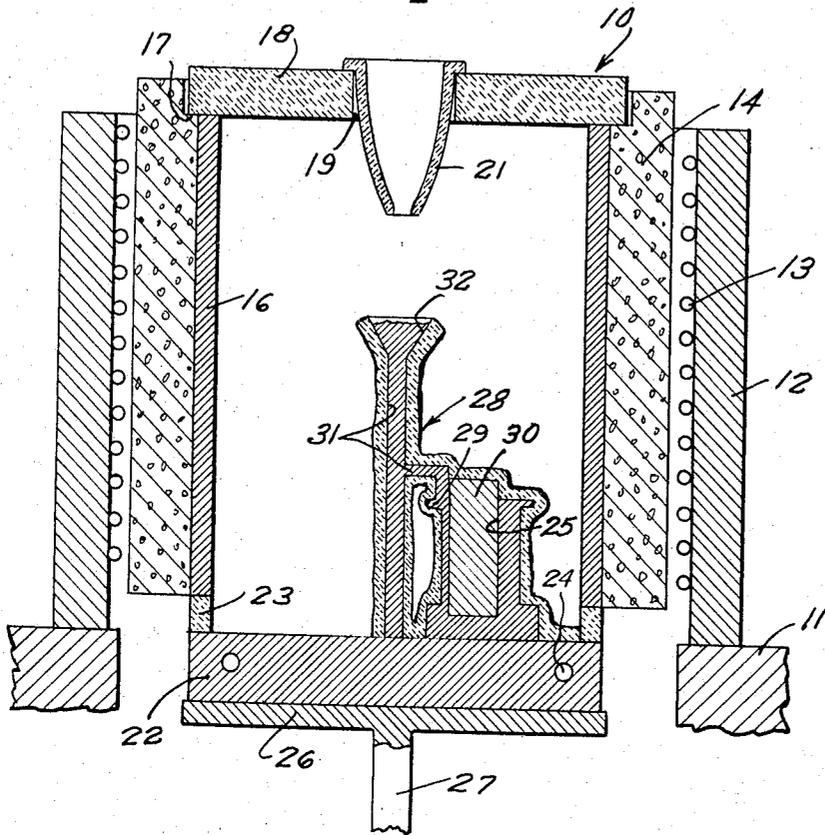
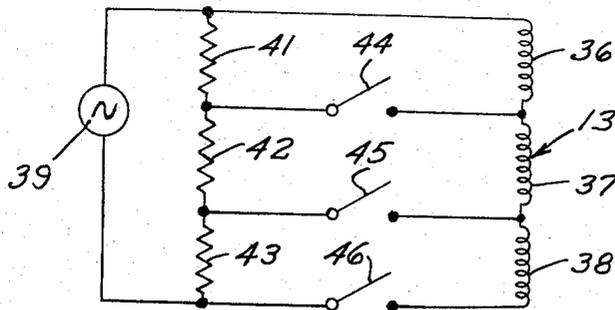


Fig. 2



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**METHOD FOR CASTING HIGH TEMPERATURE ALLOYS TO ACHIEVE CONTROLLED GRAIN STRUCTURE AND ORIENTATION**

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**ABSTRACT OF THE DISCLOSURE**

Method and apparatus for casting of high temperature allows of controlled grain structure and orientation, wherein a porous mold is preheated prior to introduction of the molten metal such that the temperature at the bottom of the mold is the lowest and that at the top of the mold is the highest, pouring the molten metal into the preheated mold, and solidifying the melt therein under conditions of controlled cooling.

The present invention relates to methods and apparatus for the casting of high temperature alloys and, more specifically, to the production of castings having controlled grain structure and exceptional soundness. In a specific embodiment of the present invention, the invention is applied to the production of columnar castings which have been found to be particularly desirable in articles such as jet engine blades and vanes which are subject to extreme heat and thermal cycling.

The presence of columnar zones in castings has been recognized for some time, but until recently, this type of structure was considered a defect and not nearly so desirable as the equiaxed structure. In recent years, however, the properties of columnar structures have undergone re-examination and it has now been determined that in some applications, the columnar structures are markedly superior to equiaxed structures. For example, it has been found that the high temperature properties of columnar structures are superior, particularly in fracture resistance and ductility under creep loading conditions.

Columnar structures are formed by the unidirectional growth of dendrites during solidification. The relationship between the dendritic structure and the columnar grains is not exact. Each columnar grain is usually composed of more than one dendrite, and the number may vary from a few to several hundred. The interdendritic spacing is related to the solidification rate only. Columnar grain size, however, may be affected by factors other than the solidification process, such as ordinary grain growth. Despite these differences, the most convenient approach for the examination of columnar structure formation is through the study of dendrites formed during solidification.

The primary requirement for the formation of a parallel dendritic structure is the presence of a unidirectional thermal gradient. When the metal first enters the mold, the initial solidification occurs at the mold wall due to a chill effect, assuming the mold wall to be below the solidification temperature of the metal. This chill zone consists of many fine dendrites having a random orientation. The initial freezing releases the heat of fusion, resulting in some temperature rise locally, arresting the chill zone formation. At the interface of the chill zone and the melt the dendrites begin to grow into the melt at a rate dependent upon the amount and depth of the supercooling.

Initially, all dendrites at the chill zone-melt interface grow at equal rates, since equal supercooling is present. However, those oriented parallel to the thermal gradient are growing into an area of continued supercooling.

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Those oriented unfavorably cannot advance as rapidly in the direction of the thermal gradient, since only a component of the growth velocity is aligned with this gradient. The dendrites growing parallel to the gradient, since they have already undergone some growth, will give off a latent heat of fusion, due to the freezing process. This heat of fusion increases the temperature at the base of the dendrites and decreases the amount of supercooling available for growth of the more unfavorably oriented neighbors. In this manner, the growth of the misoriented dendrites is stifled, and only those aligned with the thermal gradient will undergo significant growth.

The aligned dendrites formed will display a preferred crystallographic orientation, depending on the crystal system, and, in more complex systems, on the particular metal or alloy. This behavior can be rationalized in the following way. Crystals growing into a melt are formed with the planes of atomic density forming the faces. In the face centered cubic metals, for example, the faces of the crystals would form an octohedron bounded by the (111) planes. The direction of maximum growth coincides with the maximum dimension of this octohedron, the (100) plane. It would be expected, then, that the (100) plane would be aligned parallel to the predominant thermal gradient and this has been observed in numerous cases. In the more simple crystal systems, the body centered cubic and the face centered cubic, the direction of preferred orientation, (100) in each case, is generally the same regardless of the metal involved. In systems of noncubic symmetry the particular metal or alloy will determine the direction. In close packed hexagonal systems, for example, the  $c/a$  ratio is an important factor in determining the direction of preferred orientation.

The solidification of alloys proceeds along the lines mentioned previously, but in a somewhat more complex mechanism since concentration gradients as well as thermal gradients may exist during solidification.

Casting variables affect columnar structures through their influence on the thermal or compositional gradients developed in the mold. These variables include metal superheat, initial mold temperatures, the use of chills or exothermic materials, and the alloy composition. Variation of the thermal gradients within the range of columnar formation also influences the structure of the casting. If a steep thermal gradient exists, the rapid rate of heat extraction requires rapid solidification. At the same time the relatively short supercooled layer restricts the length of the dendrites extending into the melts. During solidification mass transport of solute between the dendrites must take place. Since the overall solidification rate is determined by the rate of heat removal, the diffusion distances must be reduced to permit the proper distribution of solute to take place. This is accomplished by increasing the number of dendrites, thus reducing the interdendritic distances. It has been experimentally verified that as the solidification rate increases, the interdendritic spacing decreases at a rate proportional to the square root of the solidification rates.

The consequences of this behavior are evident in extended columnar structures. As the distance from the mold wall increases, the dendritic spacing also increases. This can probably be attributed partially to the elimination of unfavorably oriented dendrites, but the major influence responsible is the decrease in thermal gradients as the dendrite-melt interface moves through the mold.

Comparative tests between equiaxed and columnar castings indicate that the columnar casting has marked advantages for certain applications. The high temperature strength and ductility of the columnar structures is generally superior to the equiaxed structure, and may be attributed to the preferential occurrence of gas porosity at

grain boundary locations. In the equiaxed structures the gas porosity is distributed randomly, following a grain boundary pattern. As a result, intergranular fractures occur with low ductility. In the columnar structure the grain boundaries are oriented parallel to the growth direction. Accordingly, the porosity has little or no influence on ductility. The improvement in ductility can be attributed to several factors. The segregation normally associated with equiaxed grains is reduced by the columnar solidification process. The conditions necessary to form columnar structures are identical to those required for proper feeding. Thus, microshrinkage is almost completely eliminated. The primary reason for improved ductility, however, appears to be the elimination of grain boundaries perpendicular to the stress axis. This prevents the normally brittle intergranular type of fracture, permitting a great amount of deformation to occur prior to failure.

Numerous techniques have heretofore been suggested for securing columnar castings with the columnar grain growth in the direction of major stress. These techniques have been invariably proved expensive, however, because the heat cycles were very long. It was not unusual, for example, to require a heat cycle of 6 hours to process a jet engine blade.

One of the objects of the present invention is to provide an improved method for casting which makes it possible to substantially reduce the time involved in growing columnar grain structures.

Another object of the invention is to provide an improved method for producing castings of intricate shape with columnar structures having exceedingly large length to width ratios.

Another object of the invention is to provide an improved method for securing highly directional solidification in castings, while obtaining maximum casting integrity.

A further object of the invention is to provide an improved apparatus for casting molten metals while controlling the grain orientation and improving soundness.

A further object of the invention is to provide an apparatus which allows the casting mold to expand freely, thereby preventing the occurrence of cracked molds and ceramic inclusions.

Other objects and features of the present invention will become apparent to those skilled in the art from the following detailed description, and reference to the accompanying drawings.

In accordance with the present invention, there is provided a method of casting which includes positioning a mold, usually of the porous shell mold type, within an induction heated enclosure while secured to a highly heat conductive chill plate, establishing a temperature differential in the enclosure ranging from a temperature below the melting range of the metal to be cast in the vicinity of the chill plate to a temperature in excess of the melting range in the vicinity of the upper end of the mold, and then pouring molten metal into the mold. The induction heating elements are composed of a plurality of induction coils which are arranged to be energized in sequence, so that the temperature at various locations about the molding assembly can be selectively varied as the chilling of the casting proceeds. The selective partial deenergization of the induction heating elements therefore serves progressively to establish directional solidification of the metal within the mold. Additional benefits are achieved if the mold is repositioned axially within the enclosure during the interval in which the inductance heating elements are being partly deenergized.

Referring to the drawings, FIGURE 1 is a somewhat schematic cross-sectional view of an assembly which can be used for the purpose of the present invention; and

FIGURE 2 is a schematic circuit diagram of the induction heating assembly employed in FIGURE 1.

In FIGURE 1, reference numeral 10 indicates generally

a furnace structure of the type embodying the principles of the present invention. The furnace structure 10 includes a support surface 11 and a cylindrical outer frame 12 secured to the support surface 11. Inductance heating coils generally indicated at reference numeral 13 are positioned between the frame 12 and a refractory insulating sleeve 14 composed of a highly refractory firebrick or other thermal insulating composition. At the inner periphery of the sleeve 14 there is positioned a susceptor 16 composed of graphite or the like. The upper end of the sleeve 14 is relieved to provide an annular shoulder 17 upon which a refractory cover plate 18 is arranged to seat to close off the top of the mold enclosure. The cover plate 18 is provided with an aperture 19 through which a refractory funnel 21 may be inserted for introducing molten metal into the interior of the mold enclosure.

The bottom of the mold enclosure consists of a highly heat conductive chill plate 22 composed of copper or other similarly highly conductive metal. The chill plate 22 is separated from the bottom of the susceptor 16 by means of a ceramic ring 23. The chill plate 22 has passages 24 therein for the purpose of circulating a coolant therethrough to secure the maximum chilling effect.

The chill plate 22 is secured to a platform 26 arranged for vertical movement with respect to the molding enclosure, the platform 26 extending from a shelf 27 which is secured to a hydraulic cylinder or the like (not shown) to effect such relative movement.

Disposed within the mold enclosure is a ceramic shell type mold generally indicated at reference numeral 28. Such molds may be made by any of a variety of precision investment mold making processes. The typical mold 28 may include a casting cavity 29 fed by a runner 31 and a sprue 32 which underlies the funnel 21.

The casting cavity for the mold has been identified at numeral 25, and a ceramic core 30 is shown surrounded by the metal in the cavity 25. As shown, the chill plate 22 forms a bottom closure for the casting cavity 25.

As illustrated in FIGURE 2, the inductance heating element 13 consists of a plurality of individual inductance heating coils, there being three coils 36, 37 and 38 shown in FIGURE 2 for purposes of convenience. These coils are selectively energized from an alternating current source 39 across which there is provided a voltage dividing network consisting of a plurality of resistors 41, 42 and 43 in series. Switches 44, 45 and 46 are inserted in the respective coil circuits to permit splitting the power from the source 39 and energizing 1, 2, or all of the three inductance coils illustrated.

In the operation of the furnace, the ceramic mold 28 is first secured to the chill plate 22 by means of bolts or the like beneath the funnel 21. The mold assembly is then preheated to a very high temperature in a gradient fashion. For example, for an alloy melting at about 2400° F., the mold near the water cooled chill plate 22 may be at a temperature near 2000° F., while the upper portion of the mold, removed from the chill plate 22, the temperature may be about 2700° F. The provision of the split coil heating system makes it quite easy to accomplish this temperature differential. After the temperatures have been established the metal is poured in through the funnel 21, and from this point on, the solidification of the metal is controlled by adjustment of the energization of the coils 36, 37 and 38 alone, or in combination with a gradual lowering of the mold assembly by partial withdrawal of the chill plate 22 from the position shown in FIGURE 1 as the directional solidification proceeds. In this way, it is possible to solidify an extremely thin walled casting directionally, producing the desired columnar structure and extreme soundness. It is entirely possible with this method to produce castings of extremely intricate shape and columnar structures having length to width ratios of 100 to 1 or even more. Furthermore, it is possible to feed thick sections of castings through very

thin sections in a highly directional fashion to control the soundness and the grain structure. Since the mold is allowed to expand freely within the mold enclosure, the possibility of cracked molds and ceramic inclusions is minimized. What is more, the method here involved reduces the time cycles by a factor of at least 50% of those employed previously.

The following specific example will illustrate the application of the invention to a specific casting procedure.

*Example*

A jet engine vane was poured into a mold assembly of the type shown in FIGURE 1. The chill plate 22 consisted of a copper block which was water cooled, and the mold assembly was bolted down to the chill plate prior to heating. The mold was heated to 2650° F. as measured at the top of the mold cavity, and held for 30 minutes. A high temperature nickel base alloy was poured into the mold at 2850° F. The controlled temperature was dropped immediately to 2550° F. and held for 10 minutes after which time, the entire mold assembly was dropped about 1 inch out of the graphite susceptor 16, and the temperature from this point on was maintained through the use of a split coil power system in which power was provided to the upper two thirds of the coil. The poured casting was cooled gradually in steps of approximately 25 minutes per 50° down to 2200° F., at which point the power was turned off. The hot poured casting was then dropped out of the susceptor and removed from the copper chill plate. The entire cycle took only slightly in excess of 3 hours, whereas times in excess of 6 hours were previously required by other methods.

It should be evident that various modifications can be made to the described embodiments without departing from the scope of the present invention.

I claim as my invention:

1. The method of casting which comprises positioning a porous ceramic mold within an induction heated enclosure, establishing a temperature differential in said enclosure ranging from a temperature below the melting range of the metal to be cast at one end of the enclosure to a temperature in excess of said melting range at the opposite end of said enclosure, then pouring the molten metal into said mold, and thereafter selectively partially deenergizing the induction heating on said enclosure progressively to establish directional solidification of the metal within said mold.

2. The method of claim 1 in which said mold is repositioned axially within said enclosure during the interval in which the induction heating is being partially deenergized.

3. The method of casting which comprises positioning a porous ceramic mold within an induction heated enclosure, establishing a temperature differential in said enclosure ranging from a temperature below the melting range of the metal to be cast at one end of the enclosure to a temperature in excess of said melting range at the opposite end of said enclosure, then pouring the molten metal into said mold, thereafter selectively partially deenergizing the induction heating on said enclosure progressively to establish directional solidification of the metal within said mold, continuing the partial deenergization until the temperature of the enclosure drops below the melting range of the metal, and then terminating the induction heating.

4. The method of casting which comprises positioning a porous ceramic mold within an induction heated enclosure and secured to a highly heat conductive chill plate,

establishing a temperature differential in said enclosure ranging from a temperature below the melting range of the metal to be cast in the vicinity of said chill plate to a temperature in excess of said melting range in the vicinity of the upper end of said mold, then pouring the molten metal into said mold, and thereafter selectively partially deenergizing the induction heating on said enclosure progressively to establish directional solidification of the metal within said mold.

5. The method of casting which comprises positioning a porous ceramic mold within an induction heated enclosure and secured to a highly heat conductive chill plate, establishing a temperature differential in said enclosure ranging from a temperature below the melting point of the metal to be cast in the vicinity of said chill plate to a temperature in excess of said melting range in the vicinity of the upper end of said mold, then pouring the molten metal into said mold, and thereafter selectively partially deenergizing the induction heating on said enclosure to establish directional solidification of the metal within said mold, continuing the partial deenergization until the temperature of the enclosure drops below the melting range of the metal, and then terminating the induction heating.

6. The method of casting which comprises positioning a thin walled, relatively porous open-ended mold on a highly thermally conductive surface in a furnace in spaced relation to a surrounding radiating body, heating said radiating body unequally to provide zones of different temperatures within said mold, pouring molten metal into said mold while said different temperature zones exist therein, and controlling the application of heat to the resulting casting while solidification of said casting is progressing.

7. The method of casting which comprises positioning a thin walled, relatively porous open-ended mold on a highly thermally conductive surface in a furnace in spaced relation to a surrounding radiating body, heating said radiating body to provide zones of different temperatures within said mold, pouring molten metal into said mold while said different temperature zones exist therein, and moving said mold relative to said zones during solidification of the resulting casting to thereby control the temperature gradients in said mold during such solidification.

8. The method of casting which comprises positioning a thin walled, relatively porous open-ended mold on a highly heat conductive surface in a furnace in spaced relation to a surrounding radiating body, heating said radiating body unequally to provide zones of different temperatures within said mold, pouring molten metal into said mold while said zones exist therein, controlling the temperatures in said zones during solidification of the casting in said mold, and moving the mold relative to said zones as such solidification proceeds.

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