

[54] **APPARATUS FOR UNIDIRECTIONALLY
 SOLIDIFYING METALS**

[75] Inventors: **Milton E. Kirkpatrick**, Palos Verdes,
 Calif.; **Thomas S. Piwonka**, North
 Canton, Ohio; **Bruce D. Marcus**, Los
 Angeles, Calif.

[73] Assignee: **TRW**, Redondo Beach, Calif.

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[58] Field of Search **164/60, 338; 165/30,
 165/64, 105**

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Primary Examiner—J. Spencer Overholser

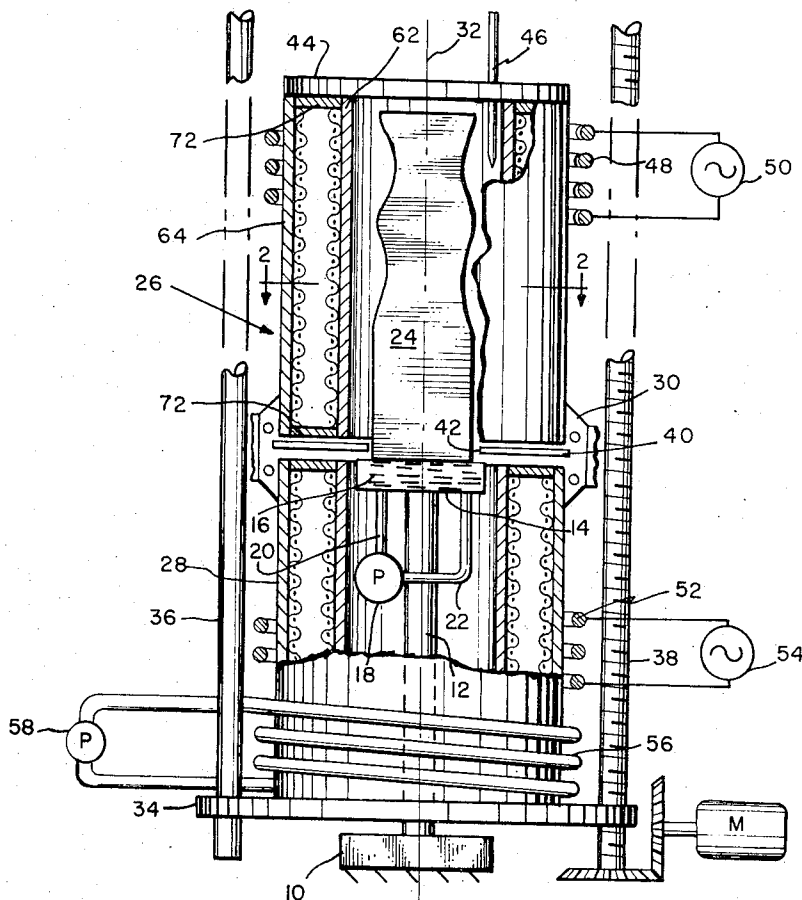
Assistant Examiner—John E. Roethel

Attorney—Daniel T. Anderson et al.

[57] **ABSTRACT**

A pair of annular heat pipes are arranged end-to-end around a casting mold. One of the heat pipes is heated above the liquidus temperature of the alloy to be cast, while the other heat pipe is heated below the solidus temperature of the alloy. A chill is placed at one end of the mold to cool the alloy unidirectionally. A sharp temperature gradient that is virtually a step function is produced at the junction of the two heat pipes which results in greater control over the region of solidification of the alloy as the heat pipes are moved to cool and solidify the alloy.

8 Claims, 2 Drawing Figures



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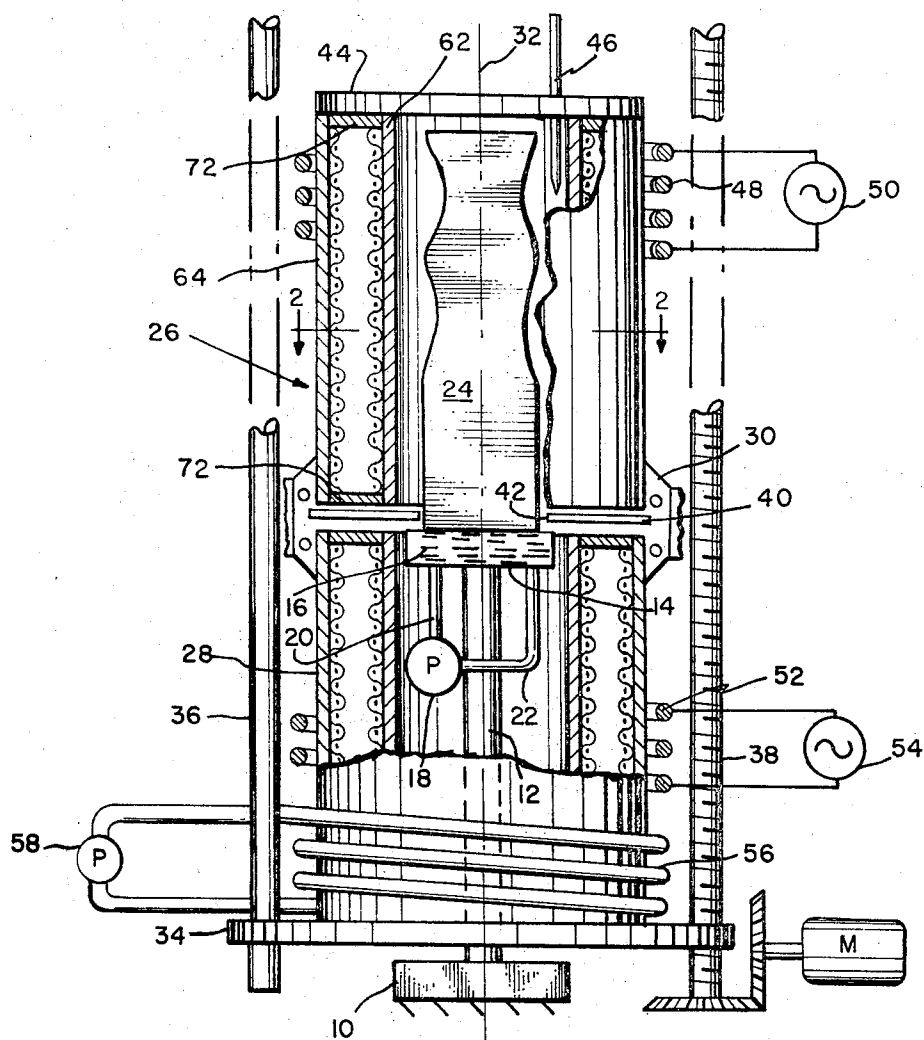


Fig. 1

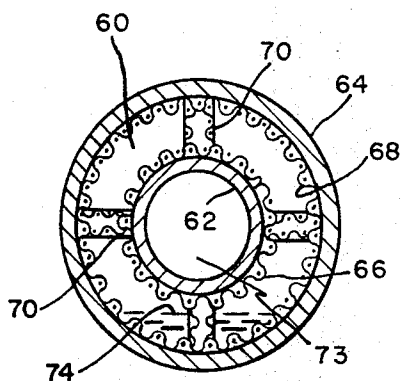


Fig. 2

Milton E. Kirkpatrick
Thomas S. Piwonka
Bruce D. Marcus
INVENTORS

BY *Jerry A. Dinardo*

AGENT

APPARATUS FOR UNIDIRECTIONALLY SOLIDIFYING METALS

This is a continuation of application Ser. No. 34,415, filed May 4, 1970, now abandoned.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to the art of metal casting and more particularly to improved apparatus for unidirectionally solidifying metals, especially metal alloys.

2. Description of the Prior Art

It is known in the metal casting art that if the mold is heated above the melting point of the metal being cast, except at one end where it is chilled, the heat will flow from the metal in the direction of the chilled end and the metal will solidify unidirectionally. The resulting metallurgical structure of the metal will have grains or crystals that are likewise aligned in the direction where heat flow occurred. Certain properties of unidirectionally solidified metals are better than those that are solidified conventionally. For example, unidirectionally solidified castings are used to make improved turbine blades. Furthermore, if a eutectic alloy is unidirectionally solidified, the resulting structure will be a naturally produced composite of aligned needles or platelets bound together within a matrix of bare metal.

In certain cases, it is desirable that the metal casting be in the form of a single crystal. This is also a desirable structure for turbine blades. To achieve this type of metallurgical structure, it is necessary in the metal cooling process that a very steep thermal gradient be maintained across the liquid-solid interface as it moves from the cold end to the hot end. A principal object of this invention is to increase the thermal gradient acting upon the liquid-solid interface of a metal subjected to unidirectional solidification.

SUMMARY OF THE INVENTION

In accordance with the improved metal casting apparatus of the invention, a first annular heat pipe, arranged along a longitudinal axis, is provided with a heater means for establishing within the heat pipe a first uniform temperature above the liquidus temperature of the alloy to be cast. A second annular heat pipe is arranged end-to-end with the first one and with means for establishing within the second heat pipe a lower uniform temperature below the solidus temperature of the alloy.

A mold is placed within the first higher temperature heat pipe, with a cooling means or chill located near the junction of the two heat pipes. Means are provided for moving the two heat pipes together along the longitudinal axis so that the mold effectively moves out of the hotter heat pipe and into the cooler one.

Because the heat pipes are substantially isothermal along their lengths, each with different temperature, the temperature gradient at their junction is rather steep and approaches a step function. The thermal gradient is considerably sharper than that produced by conventional means.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a diagrammatic view of casting apparatus for unidirectionally solidifying metal alloys according to the invention; and

FIG. 2 is a section taken along line 2—2 of FIG. 1.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to the drawing, there is shown a rigid base 10 and an upstanding elongated support member 12 affixed thereto. The top of the support member 12 supports a chill block or plate 14 of thermally conductive material, such as copper. The chill block 14 is preferably provided with internal passageways through which extend a series of conduits 16 for conducting a cooling fluid. The coolant may be supplied from a source 18 which pumps the fluid through the conduits 16 between an inlet tube 20 and an outlet tube 22.

On top of the chill block 14 is supported a ceramic mold 24 which may be open at both ends. The mold 24 has the shape of the desired article to be cast, such as turbine blade.

In accordance with the invention, the mold 24 is surrounded by two annular heat pipes, one being a high temperature heat pipe 26 and the other a low temperature heat pipe 28. Both heat pipes 26 and 28 are as long as the mold 24 and are joined end to end by a suitable connecting means 30. The heat pipes 26 and 28 may have a similar geometric configuration, such as the same cross-section, be it circular, square, or rectangular, and may have substantially the same length. Thus, they may have the same symmetry about a longitudinal axis 32 and have a combined length about double that of the mold 24.

The heat pipes 26 and 28 are movable vertically along the longitudinal axis 32. Longitudinal movement may be provided by mounting the lower heat pipe 28 on a platform 34 and raising or lowering the platform 34 along a guide rod 36 by means of a driven screw 38. As will be explained more fully below, the heat pipes 26 and 28 must be moved a sufficient distance to raise the upper heat pipe 26 from an initial position where it entirely encloses the mold 24 to a second position where the mold 24 is entirely removed therefrom.

An annular radiation baffle plate 40 is mounted between the adjacent ends of the two heat pipes 26 and 28. The baffle plate 40 is made of refractory material or high melting point metal, such as molybdenum, to protect the chill block 14 from the high temperature of the upper heat pipe 28 and to aid in sharpening the thermal interface between the two heat pipes 26 and 28. The baffle plate 40 is formed with a central opening 42 large enough to pass the mold 24 when the heat pipes 26 and 28 are moved vertically.

An additional radiation baffle plate 44 is mounted on top of the upper heat pipe 26, closing the opening thereof to prevent loss of heat from the internal regions of the upper heat pipe 26. The radiation baffle plate 44 may comprise a solid plate as shown, in which case it would need to be moved to permit the charging of the mold 24 with molten metal. Alternatively, the baffle plate 44 would not require movement prior to charging the mold 24 if it is provided with a central opening through which the molten metal can be poured. The baffle plate 44 may, in addition, be independently heated to aid in heating the mold 24. In this case, the baffle plate 44 may itself be a heat pipe.

A thermocouple 46 extending through the upper baffle plate 44 monitors the temperature of the upper heat pipe 26. The upper heat pipe 26 is heated by an induction coil 48 which receives energy from a source 50 of radio frequency current. The induction coil 48 may

comprise only a few turns encompassing a small portion of the length of the heat pipe 26. The reason for this is that the heat pipe is such an efficient thermal conductor that, if heat is applied to only a small area thereof, the heat is readily transmitted over the entire volume, and when thermal equilibrium is reached, it becomes an isothermal surface. As an alternative to induction heating, electrical resistance heating or any other suitable form of easily controllable heat may be used. Whatever form of heating energy is used, it must be sufficient to heat the upper heat pipe 26 and maintain it at the operating temperature for which it is designed, which must be a temperature above the liquidus temperature of the alloy to be cast. For some of the nickel base super alloys, the liquidus temperature is around 2500°F.

The lower heat pipe 28 is similarly provided with a heater coil 52 that receives radio frequency energy from a source 54. The heating energy supplied to the lower heat pipe 28 must be sufficient to heat it and maintain it at the operating temperature for which it is designed, which in this case is a temperature below the solidus temperature of the alloy being cast, say below 2000°F for the nickel base super alloys. The heater coil 52 is spaced a short distance from the lower end of the lower heat pipe 28 so as to accommodate a cooling means such as a coiled tube 56. The cooling tube 56 is supplied coolant fluid from a source 58. The purpose of the cooling tube 56 is to remove excess heat from the casting mold as the lower heat pipe 28 is raised along the length of mold 24, thereby tending to keep heat pipe 28 below the solidus temperature of the alloy being cast.

Each of the heat pipes 26 and 28 is annular in configuration and is preferably one of the kind disclosed in the copending application of Milton E. Kirkpatrick, Ser. No. 797,725 filed Jan. 31, 1969, entitled "Heat Transfer Device." The details of construction of only the upper heat pipe 26 will now be described, it being understood that the construction of the lower heat pipe 28 will be similar.

Referring now to FIG. 2, the "heat pipe" 26 includes concentric inner and outer cylindrical metal tubes 62 and 64, respectively. The space between the tubes 62 and 64 forms an annular chamber 60. The surfaces of the tubes 62 and 64 disposed within the annular chamber 60 are covered with linings 66 and 68 or porous wick material. The two wick linings 66 and 68 are spaced apart and joined together by short spacer elements 70 of wick material that are spaced along the length of the tubes 62 and 64.

The annular chamber 60 is closed at both ends of ring-like cover plates 72, which leave an isothermal working space 73 open within the heat pipe 26 for easy access from the outside. The annular chamber 60 is evacuated of non-condensable gases, such as air, and contains a vaporizable working fluid 74 of sufficient quantity to wet the entire wick material by capillary action. The specific fluid depends upon the operating temperature desired for the "heat pipe" 26.

The wick material for the linings 66 and 68 and spacer elements 70 may be in the form of sintered metal, wire screens, or other porous compacts having voids or openings of capillary size and capable of transporting the vaporizable working fluid 74.

In the operation of the heat pipe 26, the heater coil 48 is energized to heat the portion of the annular "heat

pipe" 26 surrounded thereby. The working fluid 74 heated thereby vaporizes and the vapor carries away from the high heat flux region thermal energy equivalent to the heat of vaporization. The vapor migrates through the annular chamber 60 where it condenses on all interior surfaces that are below the temperature of the vaporizing surface, thereby giving up the heat of vaporization to and raising the temperature of all the cooler surfaces. Continuous vapor flow paths are provided along the annular extent of the annular chamber 70 by means of the radial and linear spacing between the spacer elements 30. The condensed working fluid 74 is then transported by capillary action through the wick material from these condensing regions to the vaporizing region or high heat flux input zone, where the working fluid 74 again vaporizes.

By means of this closed loop process, thermal energy supplied by the heater coil 48 is transported and delivered to any and all cooler interior regions of the chamber 70. The result is that the entire surface of the "heat pipe" 26 quickly becomes an isothermal surface when operating in the temperature range determined by the working fluid, and the volume within the isothermal working space 73 is uniform in temperature along the entire length of the "heat pipe" 26.

For a specific working fluid, there is a range of equilibrium temperatures over which the annular heat pipe will provide isothermal conditions. The lower limit of the equilibrium temperature range is determined by the thermodynamic properties of the working fluid, namely the vapor pressure and the heat of vaporization. The upper limit of the equilibrium temperature range is determined by the mechanical ability of the device to withstand the positive pressures of the vapor relative to the surrounding atmosphere.

For casting the nickel base super alloys referred to above, the upper or high temperature heat pipe 26 and the wicks therefor may be fabricated from a columbium base alloy such as 99 percent columbium and 1 percent zirconium, or alloy C-103 containing 89 percent columbium, 10 percent hafnium, and 1 percent titanium. The working fluid may be lithium. For the lower or low temperature heat pipe 28 and the wicks therefor, the material may be stainless steel and the working fluid may be sodium.

The operation of the metal casting apparatus will now be described. With the heat pipes 26 and 28 and ceramic mold 24 in the position shown in FIG. 1, the heater coils 48 and 52 are energized. When the heat pipes 26 and 28 have reached their respective isothermal equilibrium temperatures and the mold 24 has reached the same temperature, the upper baffle plate 44 is removed and molten metal or alloy is poured into the mold 24. Upon striking the chill block 14, the molten metal immediately solidifies as a layer and forms a seal between the chill block 14 and the mold 24 so that the molten metal poured on top of the solidified metal layer will not leak out. When the mold 24 is filled with molten metal, the upper baffle plate 44 is replaced.

With the mold 24 and heat pipes 26 and 28 in their relative positions shown in FIG. 1, the upper heat pipe 26 is an isothermal surface having a temperature above the liquidus temperature of the molten metal. The ceramic mold 24 and the molten metal therewithin are subjected to that uniform temperature along their vertical length, and they would also be at that same uniform temperature except for the presence of the chill block

14 which subjects the base of the mold 24 and the solidified metal layer to a much lower temperature. A thermal gradient is immediately established in the molten metal, which tends to conform to the sharp thermal gradient established outside the mold 24. Externally of the mold 24, the sharpness of the thermal gradient is due to the uniform isothermal temperature of the upper heat pipe 26 which subjects the mold 24 to heat by radiation and the abrupt drop in temperature at the chill block 14 which extracts heat from the mold and metal by conduction.

Thus, in the initial stages of metal solidification, the metal is subjected to cooling preferentially in the direction of the chill block 14, or to unidirectional cooling in that direction. This gives rise to the formation and growth of crystals or grains that are oriented in the vertical direction. In the mold 24, the metal is partly solidified next to the chill block 14, the bulk of it is molten above the liquidus temperature, and at the interface of the molten and solid there is an intermediate zone that is partly liquid and partly solid where the grains or crystals are forming.

The lower heat pipe 28 is maintained as an isothermal surface at a temperature below the solidus temperature of the metal. At the junction of the two heat pipes 26 and 28 there is a sharp thermal gradient equal to the difference in isothermal temperatures of the heat pipes 26 and 28.

In order to solidify the molten metal, the heat pipes 26 and 28 are jointly moved vertically upwards to subject the mold 24 and metal therein to a moving sharp thermal gradient. As the heat pipes 26 and 28 move up the length of the mold 24, the mold 24 loses by thermal radiation the thermal energy it received from the upper heat pipe 26. No longer heated by the upper heat pipe 26, the cast metal transfers its heat to the chill block 14 by conduction or by radiation to the lower heat pipe 28 which moves into the areas of the mold 24 previously occupied by the upper heat pipe 26. As the metal is solidified, the lower heat pipe 28 provides cooling in the radial direction of the metal casting lying below the liquid-solid interface. However, radial cooling of the metal after it has solidified does not affect the unidirectional metallurgical structure that was established as the metal solidified in the region of the sharp thermal gradient.

The rate at which the heat pipes 26 and 28 traverse the mold 24 may be adjusted for each specific alloy to provide unidirectional growth of the solidified metal as well as economy in processing time.

When the heat pipes 26 and 28 have traversed the entire length of the mold 24, the power to the heater coils 48 and 52 may be shut off and the mold allowed to cool further to the ambient temperature. The cooling provided by the coiled tube 56, as well as the conductive cooling provided by the chill plate 14, contribute to the cooling process which terminates at or near ambient temperature.

The upper and lower heater coils 48 and 52 may be attached to their respective heat pipes 26 and 28 so that they move along with them. Alternatively, they may remain fixed while the heat pipes move, provided they are properly located to heat the pipes in all positions. The coiled tube 56 is preferably fixed to the lower end of the lower heat pipe 28.

Some of the alloys which are used for turbine blades are as follows:

Alloy	Nominal Composition %	Melting Range °F
M252	0.16C, 0.02Mn, 0.08Si, 19.1Cr, 9.95Co, 9.7Mo, 2.5Ti, 1.1Al, 0.06Zr, 2.1Fe, Balance Ni	2450 - 2500
IN-100	0.18C, 10Cr, 15Co, 3Mo, 5.5Al, 5Ti, 1.0V, 0.05Zr, 0.015B, Balance Ni	2300 - 2400
U-700	0.15C, 3.25Al, 3.5Ti, 5.1Mo, 15Cr, 18.5Co, 1.0Fe, 0.1B, Balance Ni	2200 - 2550
Inconel 713	0.14C, 0.25Mn, 0.5Si, 13Cr, 9.5Mo, 0.75Ti, 6.0Al, 2.5Fe, 2.3Cb+Ta, Balance Ni	2300 - 2350

It has been found that, for best results with the above alloys, the intermediate mushy zone (the two phase region where solid and liquid coexist) between the liquid and solid metal should be kept to a minimum. The thermal gradient thereby desired, which is a few hundred degrees per inch for the above alloys, is easily achieved by means of the invention.

We claim:

1. In combination:

- a first and second annular heat pipes joined together in close end-to-end spaced apart adjacency and having central passageways substantially aligned along a common axis;
- means including first and second heater means coupled separately to said first and second heat pipes respectively for establishing isothermal conditions in said heat pipes along said axis, with said first heat pipe at a higher equilibrium temperature than said second heat pipe, thereby to establish along said axis a temperature profile characterized by a step function;
- means for supporting a workpiece within the central passageway defined by said first heat pipe;
- means providing relative motion between said workpiece and said heat pipes along said axis so as to cause said workpiece to move out of the passageway of said first heat pipe into the passageway of said second heat pipe, thereby causing a thermal gradient represented by said step function to traverse the length of said workpiece; and
- cooling means coupling to said second heat pipe at a location spaced longitudinally from said second heater means and controllable to remove excess heat from said workpiece when the workpiece is within the working space of said second heat pipe, thereby to minimize any reduction in the magnitude of said thermal gradient.

2. The invention according to claim 1, wherein said heat pipes are provided with different working fluids having differing vaporizing temperatures;

and further wherein said heater means comprise means for heating said heat pipes to the vaporizing temperatures of their respective working fluids.

3. The invention according to claim 2, and further including means for cooling said workpiece by conduction in a direction along said axis.

4. Metal casting apparatus, comprising:

- a first annular heat pipe having a central tubular working space arranged along a longitudinal axis and provided with means for establishing and maintaining in said first heat pipe a uniform temperature above the liquidus temperature of a desired alloy to be solidified from the molten state;
- a second annular heat pipe joined with said first heat pipe in close end-to-end spaced apart adjacency

- gency and having a central tubular working space aligned along said longitudinal axis and provided with means including heater means for establishing and maintaining in said second heat pipe a uniform temperature below the solidus temperature of said desired alloy to thereby establish a sharp thermal gradient at the junction of said heat pipes;
- c. a mold disposed within the working space of said first annular heat pipe for receiving a charge of said alloy in liquid form;
- d. means for extracting heat from a portion of said mold along a direction parallel to said longitudinal axis;
- e. means for providing relative motion between said mold and said heat pipes to cause said mold to move from one working space to the other and thereby cause the junction where said thermal gradient occurs to traverse said mold from a position adjacent to said heat extracting means to the opposite end thereof in a direction along said longitudinal axis; and
- f. cooling means coupled to said second annular heat pipe at a location spaced longitudinally from said heater means and controllable to remove excess heat from said mold when said mold is within the

working space of said second annular heat pipe, thereby to maintain said second annular heat pipe below the solidus temperature of said alloy and thereby minimize any reduction in the magnitude of said thermal gradient.

5. The invention according to claim 4, wherein said heat pipes are provided with different working fluids having differing operating temperatures, and further including additional heater means for heating said first heat pipe to the operating temperature of its respective working fluid.

6. The invention according to claim 5, wherein said heater means comprises an electrical coil wound around a portion of each of said heat pipes respectively.

7. The invention according to claim 6, wherein said heat extracting means comprises a chill block upon which said mold is supported.

8. The invention according to claim 4 wherein said cooling means comprises a tube coiled around a portion of said second heat pipe, and further including means for causing coolant fluid to flow through said coiled tube.

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