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(54) Title: IMPROVEMENTS IN AND RELATING TO METAL CASTING

(57) Abstract: Improvements in and relating to metal casting According to the invention there is provided a method of planning and controlling the low pressure casting of an object, such as a metal object, in a metal mould at a casting station, including the steps of: (a)determining the overall dimensions of the mould required to cast the object including the volume and/or density of the metal required to contain the object and absorb heat during casting and subsequent cooling via heat transfer to a cooling medium. (b)thereafter calculating the required pressure and upward flow rate of molten material from a holding crucible into the mould, (c)filling the mould with molten material from the holding crucible by applying an upward pressure to the molten material, wherein the pressure is variable in accordance with the size and shape of the metal mould as determined in step (b), (d)thereafter releasing the upward pressure on the molten material in the direction of the mould such that it returns to the holding crucible to be reheated or maintained at a required temperature, (e)thereafter removing the mould and continuing to cool the contents of the mould remote from said casting station until the cast object has solidified, and thereafter removing the cast object from the mould, the process continuing with successive empty moulds being placed in situ at the casting station for further casting of required further objects.

Improvements in and relating to metal casting

This invention relates to metal casting in a, typically metal, mould by the
5 so-called low pressure casting method in which molten metal from a furnace or
holding crucible below the mould is pneumatically forced up into it, such as by
air or inert gas pressure, whereafter the metal solidifies within the mould to form
a cast object, the mould itself sometimes including a releasing agent to allow the
cast and solidified object to be thereafter easily released.

10 A key advantage of metal moulds over sand cast moulds and moulding
techniques, such as those using the so-called lost-wax process, is that the sand
and lost-wax moulds are used only once and when the cast metal has cooled
sufficiently they are broken open to retrieve the cast metal object. Although the
sand and lost-wax processes have been reasonably successfully semi-
15 automated, more particularly where the shape of the cast object is sufficiently
simple to permit such, nevertheless there is still very large wastage of energy,
manpower and material during the process such that even where the same
mould-making materials are re-cycled for repeated use, the overall efficiency
offers significant scope for improvement. On the other hand, metal moulds
20 have, at least in theory, the ability to repeatedly mould successive castings and
are usually cooled after each moulding process, such as by the use of water
flowing through conduits within the mould such that after the cast object has
solidified and cooled sufficiently the mould can then be opened to reveal the final
form of the cast object, which is then removed from the mould and the latter,
25 after further cooling, can be reused successively.

However, amongst the known disadvantages of metal mould processes is that they require relatively expensive tooling for initial set-up and, dependent upon the specification of metal being cast, the moulds are subjected to violent thermal shock, the repeated heat assault from which can lead to relatively short mould
5 life and repeated mould replacement, thereby dissipating the theoretical benefits of metal moulds over sand and lost-wax casting.

For the foregoing and other reasons of a similar nature the use of metal moulds for repetitively producing metal castings has only proven to be commercially successful in non-ferrous applications where the mould is usually
10 made from a ferrous metal with a significantly higher melting point than the non-ferrous metal being cast and having the thermal shock resistance capabilities to enable repeated use. For ferrous castings until now, their significantly higher melting temperatures have resisted casting industry attempts to find a metal capable of withstanding the significantly higher thermal shock impact for
15 sustained repeated use; with single-shot sand and lost-wax moulds maintaining the totally dominant ferrous casting method in widespread use.

However, even though the materials from which sand moulds are made are often efficiently recycled, there is still a substantial difference between the cost of and time taken to make a new sand mould and the toxic resins that have
20 to added to the sand to make it operationally effective with the attendant reprocessing and landfill disposal implications of such toxins; combining to sustain the drive to achieve the theoretical advantages of reusing a metal mould for making the same shape of casting.

In EP1797980 a low pressure die casting apparatus is shown which is particularly advantageous for manufacturing small non-ferrous hollow objects such as taps or faucets, where the object of the invention is to increase the quality of the casting by incorporating means to rotate the mould as required before, during, and after casting. The furnace is moved upwards in a vertical sense in order to supply the die with molten metal and, after casting, the cast part is allowed to cool, whereafter the mould supporting means is moved horizontally to a mould opening station remote from the casting station. By the use of two moulds, one being prepared for casting while the other is performing casting and/or cooling thereafter, the overall process is highly efficient within the parameters of the steps available with this apparatus, although its use for producing only relatively small castings where the quality of each can be quickly established by inspection after a cast object has been allowed to cool and the mould opened, testifies to the practical difficulties inherent in producing multiple castings from metal moulds of this type. CA 705311 describes a low pressure casting method which utilises a graphite or ceramic mould, and a mechanical gate to control the flow of molten material therethrough.

The present invention is derived from the realisation that conventional methods of casting using metal moulds are heavily reliant upon empirically controlling the flow of molten metal into the mould and, thereafter, monitoring the end result once the cast object has been cooled sufficiently for it to be ejected from the mould, such that the casting process is largely mould-led in the same way that one-shot moulding processes are; whereas a different approach may be preferable so as to minimise the time taken to cast each object using

successive moulds and maximise the expected quality of each cast object when retrieved from the mould, whilst minimising the overall energy requirements of the overall process

According to a first aspect of the invention there is provided a method of planning and controlling the low pressure casting of an object, such as a metal object, in a metal mould at a casting station, including the steps of:

(a) determining the overall dimensions of the mould required to cast the object including the volume and/or density of the metal required to contain the object and absorb heat during casting and subsequent cooling via heat transfer to a cooling medium.

(b) thereafter calculating the required pressure and upward flow rate of molten material from a holding crucible into the mould,

(c) filling the mould with molten material from the holding crucible by applying an upward pressure to the molten material, wherein the pressure is variable in accordance with the size and shape of the metal mould as determined in step (b),

(d) thereafter releasing the upward pressure on the molten material in the direction of the mould such that it returns to the holding crucible to be reheated or maintained at a required temperature,

(e) thereafter removing the mould and continuing to cool the contents of the mould remote from said casting station until the cast object has solidified, and thereafter removing the cast object from the mould, the process continuing with successive empty moulds being placed *in situ* at the casting station for further casting of required further objects.

Generally it is preferred that the pressure is varied so that the upward flow rate of molten material from the holding crucible into the mould is at an at least approximately constant fill level rate or velocity, although some variation may be accommodated or indeed be desirable. Accordingly, in preferred

5 embodiments step (b) includes calculating the required pressure and upward flow rate of molten material from the holding crucible into the mould with reference to a desired fill level rate or velocity within the mould which is constant to within $\pm 20\%$, preferably to within $\pm 10\%$, more preferably within $\pm 5\%$, irrespective of the shape or volume of the mould occupied by the molten

10 material, and step (c) includes carrying the pressure so that the fill level rate or velocity within the mould is constant to within $\pm 20\%$, preferably to within $\pm 10\%$, more preferably to within $\pm 5\%$. Advantageously, step (b) includes calculating the required pressure and upward flow rate of molten material from the holding crucible into the mould with reference to a substantially constant desired fill level

15 rate or velocity within the mould, and step (c) includes varying the pressure so that the fill level rate or velocity within the mould is substantially constant.

Preferably the method further includes steps of calculating the desired freezing rate of the molten material within a thermal plug forming element mounted beneath the entrance to the metal mould, such that when the mould

20 has filled with molten material the molten material in the thermal plug forming element solidifies *in situ* to form a frozen plug in that region.

It is possible to utilise a gate to control the flow of molten material into the mould. The gate may be moveable between a closed position preventing the flow of molten material into the metal mould to an open position which permits

the flow of molten material into the metal mould. However, the present inventors have discovered that it is not necessary to provide such a gate. Instead, it has been found to be preferable that the method is performed with no gate adjacent the metal mould for controlling the flow of molten material into the metal mould, wherein the flow of molten material into and out of the metal mould during step (c) is prevented by the formation of the frozen plug. Thus, it is not required to close a gate in order to prevent the flow of the molten material into the mould prior to the formation of the frozen plug. In this way, the thermal plug-forming element acts as a 'thermal valve' for the flow of molten material into and out of the metal mould.

Advantageously, the metal mould may be formed from aluminium or an aluminium alloy, preferably an aluminium bronze i.e., an alloy of aluminium and copper.

Advantageously, the thermal plug-forming element is formed from aluminium or an aluminium alloy, preferably an aluminium bronze.

Conveniently, the molten material is injected into the mould cavity through a feed tube, such as a ceramic feed tube, acting as a conduit between the molten material to be injected and the inside of the mould, the molten material being forced up the feed tube and into the mould cavity under pressure, such as gas pressure.

The end of the feed tube adjacent the metal mould may comprise a flanged region co-operable with a moveable gate, such as a graphite gate, moveable between a closed position preventing the flow of molten material

through the feed tube to an open position permitting the flow of molten material into the mould cavity. However, it is preferred that no gate is present.

Conveniently, upstream of the casting process feed material, such as metal and metal additives such as fluxes, are first melted in a melting furnace within an inert atmosphere, such as argon, whereafter the molten material is transferred to a holding crucible substantially without exposure to ambient air and delivered into the mould cavity under pneumatic pressure at a constant fill level rate. This can help to minimise the presence of gaseous inclusions within the molten material in the mould as it freezes.

Molten material from the melting furnace is conveniently transferred to the holding crucible via a siphon tube arrangement in which molten material is initially transferred under pneumatic pressure up the tube by an amount in excess of the height of the surface of the molten material before thereafter flowing down a further part of the tube remote from the inlet end of the tube to thereafter be delivered to the holding crucible substantially without exposure to ambient air.

In a preferred embodiment of the method of the invention, the steps of moulding/casting include the steps of controlling the heat management of the cast object after casting to manage the quality of the cast metal while it is still in the mould and, separately, cooling the mould and thereafter extracting the casting. This heat management may include the process of designing the mould to include a sufficient mass of aluminium or other metal used in its construction to allow for variation in heat transfer of formerly molten but solidifying metal forming the casting so as to optimise the cast's physical properties. The heat

management control process may also be applied to improve a cast object's physical properties through the application of either, or both, computed pre-heating of the metal mould prior to casting and acceleration or deceleration of mould cooling rates after casting, for example through the use of water and air flow. This may conveniently be done at a different workstation to the workstation in which the object is initially cast, such that multiple cast objects may be at different locations with respect to each other, all undergoing the benefits of heat management until such time as they have solidified and can be safely removed from their respective moulds.

10 According to a further aspect of the invention there is provided a method of planning and controlling the low pressure casting of an object, such as a metal object, in a metal mould at a casting station, including the steps of:

- 15 a) determining the overall dimensions of the mould required to cast the object including the volume and/or density of the metal required to contain the object and absorb heat during casting and subsequent cooling via heat transfer to a cooling medium,
- b) thereafter calculating the required pressure and upward flow rate of molten material from a holding crucible into the mould with reference to a desired constant fill level rate or velocity within the mould irrespective of shape or volume of the mould occupied by the molten material,
- 20 c) calculating the desired freezing rate of the molten material within a thermal plug forming element mounted beneath the entrance to the metal mould, such that when the mould has filled with molten material the

molten material in the thermal plug forming element solidifies *in situ* to form a frozen plug in that region,

d) thereafter releasing the upward pressure on the molten material in the direction of the mould such that it returns to the holding crucible to be reheated or maintained at a required temperature,

thereafter removing the mould and continuing to cool the contents of the mould remote from said casting station until the cast object has solidified, and thereafter removing the cast object from the mould, the process continuing with successive empty moulds being placed *in situ* at the casting station for further casting of required further objects.

Further aspects of the invention include apparatus to perform the methods described, including the use of a transfer tube for transferring molten metal under pneumatic pressure from a holding crucible or ladle up into a mould. The tube itself may include a flanged upper region co-operable with a slideable mechanical gate, such as a graphite shut-off gate, defining or acting as a closure means for the mould when filled with molten or solidifying metal. In conjunction with this concept the invention also utilises the concept of a thermal plug forming element at the lowermost end of the mould, the thermal plug forming element being sized, shaped and dimensioned to permit complete solidification of metal in this region shortly after the mould has been filled with molten metal, such as within five seconds thereafter (by way of example). Thus, with this concept the flow of molten metal can be safely shut off from the inside of the mould, and the mould even removed from the casting station if required as soon as the thermal plug has formed, to assist productivity and enable variable heat management

during the initial solidification phase to optimise the cast object's physical qualities. The shutting off of the flow of molten metal can be achieved by means of the mechanical gate. However, surprisingly but advantageously, it has been found that it is not necessary to provide a mechanical gate. Rather, the flow of molten metal can be safely shut off by the formation of the thermal plug itself.

Accordingly, in a second aspect of the invention there is provided a low pressure casting apparatus for performing a method in accordance with the first aspect of the invention, the apparatus including:

- a metal mould;
- a casting station;
- a holding crucible for holding a charge of a molten material;
- a conducting arrangement acting as a conduit for the molten material from the crucible to the metal mould; and
- pressure producing means for controllably applying a pressure to the molten material in the crucible which causes the molten material to be transported along the conducting arrangement to the metal mould; and
- a control arrangement for controllably varying said pressure in accordance with the size and shape of the metal mould.

According to a third aspect of the invention there is provided a method of planning and controlling the low pressure casting of an object in a metal mould at a casting station, including the steps of:

calculating the desired freezing rate of a molten material which the object is to be formed from within a thermal plug forming element mounted beneath an entrance to the metal mould, such that when the mould has filled with molten

material the molten material in the thermal plug forming element solidifies *in situ* to form a frozen plug in that region, and

performing a low pressure casting operation without a gate adjacent the metal mould for controlling the flow of molten material into the metal mould, wherein the flow of molten material into and out of the metal mould after filling of same is prevented by the formation of the frozen plug.

According to a fourth aspect of the invention there is provided a low pressure casting apparatus for performing a method according to the third aspect of the invention, the apparatus including:

a metal mould;

a casting station;

a holding crucible for holding a charge of a molten material;

a conducting arrangement acting as a conduit for the molten material from the crucible to the metal mould; and

pressure producing means for controllably applying a pressure to the molten material in the crucible which causes the molten material to be transported along the conducting arrangement to the metal mould;

in which the conducting arrangement does not include a gate adjacent the metal mould, but includes the thermal plug forming element mounted beneath an entrance to the metal mould which enables molten material to solidify *in situ* to form a frozen plug in that region thereby preventing the flow of further molten material into the metal mould.

According to a fifth aspect of the invention there is provided a pressure casting apparatus including a pressure vessel, a crucible having a heating

arrangement, the crucible and heating arrangement being disposed within the pressure vessel for receiving a charge of metal and heating or maintaining the charge to or at a casting temperature, transfer tube means between the inside of the crucible and the outside of the pressure vessel at a mould receiving casting station, means for introducing gas under pressure into the pressure vessel to
5 thereby force molten metal along the transfer tube to a mould at the mould receiving casting station when mounted thereon, and means to reduce the gas pressure when the mould has been filled and closed to thereby permit it to be removed without leakage thereafter of molten metal from the outlet end of the
10 transfer tube.

Preferably, the heating arrangement is an induction heating arrangement, although other forms of heating may be used.

The apparatus may be further characterised in that the pressure vessel includes a closeable lid above the crucible, the mould receiving casting station is
15 on the outside of the lid and the transfer tube is substantially upright, in use.

According to a sixth aspect of the invention there is provided an apparatus for closing a mould when filled with molten metal, including a thermal plug forming element comprising a plug forming metal plate with an aperture through which molten metal is forced under pressure from an inlet end to an
20 outlet end adjacent the mould to be filled, the size and composition of the plate and aperture being chosen to ensure that when the mould has been filled with molten metal it thereafter solidifies in the aperture to form a frozen plug independent of solidification of the metal within the moulds.

The apparatus may be further characterised in that an apertured molten metal impact-resisting plate is disposed around the inlet end of the plug forming metal plate to thereby protect the plug forming metal plate from initial impact of a pressurised charge of molten metal for filling the mould. The impact-resisting plate thus provides protection for the thermal plug forming element from the impact of the molten metal. Advantageously, the impact-resisting plate has a slightly slower molten metal solidification rate than the thermal plug forming element. The impact-resisting plate may be made from a harder material than that of the plug forming metal plate. The impact-resisting plate may be made of an aluminium bronze.

The plug forming metal plate may be made of aluminium.

Whilst the invention has been described above, it extends to any inventive combination of the features set out above, or in the following description, drawings or claims.

The invention will now be described, by way of example only with reference to the accompanying drawings, in which:

Figure 1 is a schematic side elevation of casting apparatus for use in accordance with the method of the invention,

Figure 2 is a schematic side elevation of a preferred embodiment of casting apparatus according to the invention,

Figure 3 is a sectional view along the line "A-A" of Figure 2,

Figure 4 is a part cut-out perspective view of casting apparatus in accordance with a further embodiment of the invention,

Figure 5 is a complete end view of the apparatus of Figure 4 from the direction "B" shown arrowed in Figure 4,

Figure 6 is a sectional view of the apparatus of Figure 5 across the plane "C-C" in Figure 5,

5 Figure 7 is a perspective view of upper and lower ends of a feed tube in accordance with another aspect of the invention, in particular showing the guide rails for the shut-off gate,

Figure 8 is a top plan view of the feed tube of Figure 7,

10 Figure 9 is a partially cut-away perspective view of a further preferred embodiment of casing apparatus according to the invention, and

Figure 10 is a partially cut-away perspective view of the upper region of the apparatus of Figure 9.

Referring firstly to Figure 1, there is shown a general arrangement view of apparatus 1 for casting molten metal in an aluminium mould 2 comprising a
15 holding crucible or ladle 3 containing a charge of molten metal 4. The molten metal 4 is insulated by means of a refractory lining 5, such as fire brick, by which the charge of molten metal 4 can substantially retain its heat during successive casting operations. The holding crucible 3 is transportable from the position shown by means of a pair of oppositely disposed trunnions 6 engageable with
20 trunnion arms of a lifting mechanism (not shown). The holding crucible 3 is contained within a gas-tight metal pressure chamber crucible cover 7 which, similarly, has its own trunnion arms 8 so that it may be lifted into and out of engagement with a crucible floor-mounted base plate 9, and its own refractory lining 10. The pressure chamber cover 7 can be releasably locked in place

along the base plate 9 by means of quick-release catches 11 and, when so locked in place, is hermetically sealed against ambient atmosphere by means of a continuous gasket 12 surrounding an insulated floor 13 mounted between the base plate 9 and crucible 3. As such, the inside of the pressure chamber cover 7 may be pressurised or de-pressurised via a gas conduit 14 from a gas supply tank 15 and associated rotameter pressure control unit 16 and a control valve 17 which includes a vent conduit 18.

At the upper end of the pressure chamber cover 7 is a casting collar 19 onto which is mounted the aluminium mould 2, between each of which are disposed a solid aluminium thermal plug forming element 20 and a slideable graphite shut-off gate 21, through each of which are disposed inlet apertures 20a, 21a affording access to the shaped interior surface 22 of the mould 2. In this example the inside surface 22 is relatively complex and includes vertical, horizontal and inclined wall surfaces.

Between the casting collar 19 and the interior of the holding crucible 3 extends a ceramic feed tube 23 having a flanged upper end 24 enabling it to be firmly pressed against the underside of the casting collar 19 by means of an annular packing ring 25, which also acts as an insulant. The feed tube 23 is axially in-line with the apertures 20a & 21a affording access to the shaped interior 22 of the mould 2 when the graphite gate 21 is in the open position shown and, as will be apparent, liquid metal from the holding crucible 3 can be forced up the inside of the feed tube 23 in response to pneumatic pressure from the gas entering the inside of the pressure chamber cover 7 introduced from the gas conduit 14. This gas may typically be air, or an inert gas such as argon, and

the flow pressure and flow rate can be both measured and controlled via the rotameter 16 and the valve 17.

In operation, the rotameter 16, valve 17 and the slidable gate 21 are each connected to a process control computer (not shown) pre-programmed to calculate and monitor various parameters dependent upon the type of casting required and, in particular, the interior surface shape or topography 22 of the mould 2. Prior to this, the size and shape of the thermal plug forming element 20 has already been determined and may be either tailor-made for the particular mould 2 or may be selected from a set of such thermal plug forming elements 20, each having different thermal characteristics, such as having different diameters and shapes of aperture 20a and different overall thicknesses/masses, which collectively vary the amount by which molten metal flowing through the inlet aperture 20a will tend to solidify into a thermal plug in this region after the slideable gate 21 has been closed and the forced flow of metal ceases.

Before metal casting commences, the internal shape 22 of the aluminium mould 2 is determined by e.g. direct measurement or by calculation such that, at any given point, the required flow rate of incoming molten metal can be calculated in order to achieve a constant fill level rate or velocity. This information is then used to control the pneumatic pressure at any given instant during casting within the pressure chamber cover 7, with the gas pressure from the reservoir 15 being constantly measured and adjusted via the rotameter 16 and valve 17. In the example shown the internal surface 22 of the mould 2 is seen to have an initially cylindrical first portion followed by a stepped region, then a cylindrical but wider portion than the first portion, the mould then

assuming an inverted frusto-conical taper shape until it again assumes a cylindrical but even wider form, whereafter it reverts to an inwardly sloping taper, a step, then cylindrical region and finally ending in a closed taper. At each boundary change it will be apparent that the relative flow rate of the molten metal has to change if the actual fill level rate is to remain constant and, in practice, it has been found that, in the limit, there is a relationship between the velocity of fill rate, the density or viscosity of the liquid metal and the pneumatic pressure applied to it, such that by varying the pressure at any given point to match the topography of the interior 22 of the mould 2, a constant fill level rate or velocity can be achieved. This has significant advantages in minimising turbulence of the molten metal as it is being forced into the mould 2 and also ensures completeness of fill of the mould with the molten metal before the gate 21 is shut and the metal within the thermal plug inlet aperture 20a freezes to form a solid thermal plug.

Turning now to the embodiment shown with reference to Figures 2 and 3 there is shown a more sophisticated casting system suitable for long production runs where feed material such as scrap metal or metal ore is first fed into a melting furnace or crucible shown generally at 30, where the crucible vessel 31 is heated by an annular ring of electric coils 32 and is closed by an insulated crucible cover 33 movable between the hermetically sealed and closed position shown, to an open position (not shown), via a crank arm 34 operated by a hydraulic ram 35.

The melting crucible 30 is situated above a holding crucible shown generally at 36, the lower end of which is also heated by an annular ring of

electric coils 37, thereby ensuring that metal transferred from the melting crucible 30 remains molten prior to casting. The transfer of this molten metal from the melting crucible 30 to the holding crucible 36 is achieved via a ceramic double-barrelled transfer tube 38 having a "U"-shaped closed end 39, an inlet barrel 40 with an inlet 41 at the lower end thereof and an outlet barrel 42 with an outlet 43 leading directly into the interior void 44 of the holding crucible 36.

The holding crucible 36 again has a flanged transfer tube 45 for transferring molten metal under gas pressure to a movable mould 46 pivotably secured to a lifting arm 47 operable by a hydraulic ram 48.

The holding crucible 36 and the melting crucible 30 are each supplied with gas conduits 49, 50 connected to a gas regulator 51 and a gas supply tank 52, the gas itself typically being argon or some other suitably inert gas, although it will be understood that where e.g. oxidation is not problematic the gas may instead be air, such as air scrubbed of Hydrogen by pre-drying, or some other suitably available gas such as carbon dioxide.

In operation, feed material, such as scrap metal or metal ore and any suitable additives such as fluxes are placed into the crucible vessel 31 and the crucible cover 33 is then closed, with a suitable purge of gas typically being used to empty the void above the charge of material of ambient air. The charge of material is then heated in the crucible vessel 31 by the induction coils 32. In advance of this ambient air is also purged from the void 44 in the holding crucible 36 so that, in the limit, the gasses in each of the melting crucible 30 and the holding crucible 36 and in the pneumatic connection therebetween are the same such that molten metal transferred from the melting crucible 31 to the

holding crucible 36 is substantially uncontaminated, thereby enabling close control of the quality of the metal in its subsequently cast form.

Transfer of molten metal from the melting furnace 30 to the holding furnace 36 is achieved via the double-barrelled transfer tube 38 which acts in a manner similar to that of a siphon tube in that molten feed material is forced up into the inlet 41 of the inlet barrel 40 by increasing the gas pressure P1 in the void above the molten material in the crucible vessel 31 such that it rises to the closed end 39 of the transfer tube 38 and is then conducted downwards towards the exit end 43 of the exit barrel 42, although it will be appreciated that, due to the high mass of the molten material as compared to the downward pressure of the atmosphere, which could otherwise induce a siphon effect in e.g. water, continued flow of molten feed material from the melting crucible 30 requires a positive pressure being maintained within the crucible vessel 31 of, typically, in a range of 0.14 Bar to 0.7 Bar above ambient pressure. Thus, molten feed material from the melting crucible 30 can be efficiently transferred to the inside of the holding crucible 36 without exposure to ambient air, if required, which, in turn, has significant advantages for minimising and controlling the presence of unwanted inclusions or oxidation of the molten material, particularly if it is ferrous.

Once the molten material reaches the holding crucible 36 it will be apparent that it can be transferred directly into the interior of the mould 46 via the feed tube 45 in the same way as is described with reference to Figure 1 i.e. by, if necessary, an increase in the pressure P2 within the void 44 of the holding crucible 36 by suitable adjustment of the gas regulator valve 51 supplying

pressurised gas from the gas tank 52 down the conduit 49. Hence, the system described with reference to Figures 2 and 3 is particularly suitable for continuous casting of metal objects where raw feed materials such as scrap metal or metal ore can be repeatedly added to the melting crucible 30 at regular intervals as required and the holding crucible 36 regularly topped up with molten metal and any chosen additives, such other metals, carbon and fluxes. The cast objects can be the same shape, using the same shaped moulds, although it will be apparent that differently shaped moulds can be used, with suitable changes made to the plug forming elements if necessary so as to ensure rapid cooling at the entrance shortly after the moulds are filled and hence maximize production efficiency.

In both of the arrangements shown, respectively, with reference to Figure 1 and Figures 2 and 3, it has been found that there is a close relationship between the quality and consistency of cast objects and the ability to predict and control the fill level rate within the interior of the moulds 2, 46. By suitable selection of the size and shape of the thermal valve element 20 it is also possible to ensure thereafter that the molten metal is sealed within the mould 2, 46 and allowed to cool, either naturally or with assisted cooling such as by air or water after a frozen plug of metal is formed in the channel formed by the aperture 20a in the thermal valve element 20. This means that the mould 2, 46, itself, can be removed and replaced with an empty mould and then transferred from the casting station to a handling station remote therefrom, whereafter the mould can be left to cool and then opened and prepared for re-use, such as by being further cooled and, if required, supplied with for example a coating such as

a release agent, a heat transfer inhibitor or similar within the interior of the mould.

Turning now to the embodiment described with reference to Figures 4 to 8, which are particularly suitable for casting relatively small, short runs of cast objects, the general arrangement is similar to that shown with reference to Figure 1 except that in this case the holding crucible is in the form of a removable ladle 60 for containing molten metal (not shown). The ladle 60 rests on refractory lining bricks 61 on top of a generally rectilinear base 62 which includes at one end a three-legged table stand 63 onto which may be bolted a table (not shown) for carrying out various functions associated with the moulding process, depending upon what is required, including inspection.

Over and around the ladle 60 is disposed a bell-shaped pressure chamber 64 having its own refractory lining 65 and means, such as trunnions (not shown) by which it can be mechanically removed when released from attachment to the base 62 via a ring of peripherally disposed clamps 66 which engage with a flanged region 67 of the pressure chamber 64.

As with the apparatus shown in Figure 1, a centrally disposed ceramic feed tube 68 (seen more clearly with reference to Figure 6 and 7) depends from and through an aperture 69 in the upper end of the pressure chamber 64 and is supported by a flanged collar 70 itself secured to the pressure chamber 64.

As can be seen more clearly with reference to Figures 7 and 8 the flanged upper end of the feed tube 68 has a generally rectangular shut-off gate-receiving upper surface 72 having a pair of oppositely disposed guide channels 73 for receiving correspondingly shaped guide legs of a shut-off gate (not

shown) which may be simply a planar generally rectilinear gate of the type shown and described with reference to Figure 1, or may instead be an end portion of a reciprocating arm arrangement which sequentially shuts off the flow of molten metal through the central aperture 74 of the tube 68 when a mould
5 situated thereabove (not shown) is filled, the mould thereafter staying *in situ* until a thermal plug has formed i.e. until a plug of solidified metal has formed which prevents escape of molten metal within the mould after the mould has been moved from the casting station.

In operation, the ladle 60 is filled with molten metal at a remote station
10 and placed centrally on the refractory bricks 61 of the base 62 of the casting station. The pressure chamber 64 is then placed over it and secured in place by the clamps 66 with the ceramic tube 68 then being inserted into the ladle 60, whereafter a mould of the type schematically shown in Figure 1 may be placed on top of the assembly for then receiving during the casting process liquid metal
15 from within the feed tube 68. The liquid metal is forced up the feed tube 68 by pneumatic pressure applied to the inside of the pressure chamber 64 from a suitable pneumatic conduit (not shown) inserted within an inlet valve 75 extending through the base 62. Inspection windows 76 can be used to monitor the process and various sensors, such as temperature and pressure sensors,
20 may be utilised within or around the pressure chamber 64 to sense and help monitoring of the process during casting, such as by feeding sensed signals to a central processing unit which itself is linked to the pneumatic gas supply to the inside of the pressure chamber 64 to, in turn, increase or decrease the rate of flow of molten metal on the inside of the feed tube 68 in response to required

parameters of the inside of the mould so as to maintain throughout a constant fill level rate.

In this way, irrespective of the internal shape of the mould the rate of fill can be closely monitored and kept constant, thereby improving the homogeneity of the cast object and decreasing the susceptibility for turbulence and thermal shock to occur within the mould during filling, the object being to fill the mould at a constant fill level rate as slowly as possible such that, shortly thereafter, the thermal plug solidifies even if the interior of the cast object is still molten and heat is much more slowly being transferred to the surrounding metal of the mould. To assist this, it has been found that, depending upon the ultimate mechanical requirements of the cast object, close control over the crystalline structure of the finally moulded object can be exercised through the variation in temperature of the mould prior to casting and the subsequent acceleration in cooling of the mould post casting through the application of external cooling methods such as water or air, a process feature that is impracticable when using conventional sand or lost-wax casting methods.

The control of the various parameters is preferably achieved using suitable computer programming in which variables such as type of material to be cast, size and shape of the mould, and speed of casting are all monitored and managed.

Figure 9 shows a further embodiment of an apparatus, depicted generally at 90, for casting molten metal in an aluminium mould 92, which mould 92 comprises two mould halves 92(a), 92(b). The apparatus 90 comprises a holding crucible 94 which can hold a charge of molten metal (not shown). The molten

metal is insulated by means of a refractory lining 96, by which the charge of molten metal can substantially retain its heat during successive casting operations. Disposed between the refractory lining 96 and an outer steel frame of the crucible 94 are induction coils 98 which are used to supply the heat for melting the metal. The crucible 94 is mounted on a cast concrete base 100 and supported by a frame structure 102.

Disposed on the frame structure 102 is a steel footplate 104 on which is mounted a cupola structure 106. The cupola structure 106 seals against a projection of the steel footplate 104 via a high temperature rubber seal 108. The cupola structure 106 is insulated by means of a refractory liner 110, and a silica flake blanket 112 is disposed between the refractory liner 110 and the steel footplate 104. The cupola structure 106 can be releasably locked in place by means of locking structures 115.

At the upper end of the cupola structure 106 is a sprung collar 114 and collar clamp 116, on to which is mounted the aluminium mould 92. Disposed between the aluminium mould 92 and the collar clamp 116/sprung collar 114 is a thermal valve 118 in the form of a thermal plug forming element which may be formed from aluminium or an aluminium alloy such as aluminium/copper alloy. The region between the upper parts of the cupola structure 106 and the aluminium mould 92 is shown in more detail in Figure 10. A ceramic feed tube 120 extends from the interior of the holding crucible 94, through the upper part of the cupola structure 106 and into the interior of the sprung collar 114. The ceramic feed tube 120 has a flanged upper end 122 enabling it to be firmly pressed against the underside of the sprung collar 114 by means of an annular

heat-resistant gasket 124 of any suitable type, such as a fibrous gasket. An annular plate 126 is disposed between the top surface of the flanged upper end 122 of the ceramic feed tube 120 and the thermal plug-forming element 118. The plate 126 can be formed of any suitable material, such as an aluminium/copper alloy, and is intended to provide protection for the thermal plug forming element from the impact of the molten metal. The thermal plug forming element 118 and plate 126 have bores therethrough which are each axially aligned with the bore of the ceramic feed tube 120 so that the mould cavity 128 of the aluminium mould 92 communicates with the interior of the crucible 94. It will be appreciated that there is no gate arrangement between the ceramic feed tube 120 and the thermal plug-forming element 118. The collar arrangement is completed by a plurality of coil springs 130 which are disposed between the cupola structure 106 and the flanged upper end 122 of the ceramic feed tube 120 and which provides an upward bias against the flanged upper end 122 of the feed tube 120. The cupola structure 106 further comprises a port 132 to allow viewing and/or thermocouple access to interior of the apparatus, and a plurality of ports 134 which are of a suitable type to allow coupling to a source of pressurised gas and to permit venting of the apparatus. Any suitable pressurisation system, such as that described in relation to Figure 1, might be used to force molten metal from the crucible into the mould. The pressurisation system is controlled by a suitable control system (not shown).

The embodiment shown in Figures 9 and 10 can be used to perform the methods of the present invention. In this way, close control of the mould fill level rate can be accomplished. Advantageously, it has been found that the formation

of the plug can act as a thermal valve, which serves on its own to isolate the interior of the mould 92 from the feed tube 120. In other words, a shut-off gate structure is not required. The plug prevents molten metal from escaping from the mould. Once the plug has formed, the pressurisation of the crucible can be
5 reduced or completely shut off so that molten material is not transported along the feed tube, and the mould can be removed. The mould can be taken to another station for further processing of any desired kind. For example, the mould can be allowed to cool, or can be actively cooled. Alternatively, a controlled amount of heat may be supplied to the mould in order to perform an
10 annealing operation. The formation of the thermal plug is highly effective and efficient, results in energy savings, and permits flexible processing. Additionally, it reduces the time spent at the low pressure casting station performing a moulding operation.

As will be appreciated from the foregoing, the method of casting
15 according to a preferred aspect of the invention and, in particular, the use of a positive pressure method is to ensure that the mould cavity is filled completely and that, during filling, unwanted or unnecessary turbulence of the molten metal is avoided, thereby producing an homogeneous cast object having uniform properties throughout with relatively few, if any, unwanted inclusions or voids or
20 internal stresses induced by a rapid freezing of parts of the cast object, as compared to other parts which are cooled more slowly and evenly. In addition, the method combines dynamic pressure control with superior heat transfer management capabilities to require significantly fewer sprues, risers, gates and

reservoirs than for traditional ferrous casting methods, thereby typically improving casting yields.

As will be known, prior art casting techniques have tended to focus on filling the mould cavity by simple application of what is intended to be a constant
5 feed pressure, typically gravity fed, irrespective of the size and shape of the mould itself which, inevitably, leads to irregular and inconsistent thermal and mechanical properties being experienced during the casting process and subsequent cooling of the cast object. The feed pressure produced by these prior art techniques is in fact subject to variations, which exacerbate the irregular
10 and inconsistent properties of the cast objects. This, in turn, has traditionally led to only limited use of metal moulds in preferred moulding techniques, where the emphasis has generally been focussed upon making a mould of a required shape and then iteratively work towards choosing the best moulding technique for that particular mould to produce consistent castings of a required quality.

15 In contrast, the invention in one aspect prescribes in part a different approach which recognises that the pressure applied to the molten material during the casting process has to be varied in accordance with the size and shape of the mould such that, initially, the casting pressure may be at or near ambient and, during casting, it may increase to an amount slightly above that
20 required to fill the mould at a constant fill level rate/velocity, having regard to factors such as freezing of the molten metal against the sides of the mould as it is introduced and ensuring, of course, that sufficient pneumatic pressure is applied to fill the mould before the lower end around the region of the thermal plug forming element freezes to, effectively, seal the mould and its contents.

Management of the thermal processes before, during and after casting is also an important part of the inventive concepts described herein, which can lead to substantial energy and time savings as well as better quality of cast end product and longer mould life.

Claims

1. A method of planning and controlling the low pressure casting of an object, such as a metal object, in a metal mould at a casting station, including
5 the steps of:
- (a) determining the overall dimensions of the mould required to cast the object including the volume and/or density of the metal required to contain the object and absorb heat during casting and subsequent cooling via heat transfer to a cooling medium.
 - 10 (b) thereafter calculating the required pressure and upward flow rate of molten material from a holding crucible into the mould,
 - (c) filling the mould with molten material from the holding crucible by applying an upward pressure to the molten material, wherein the pressure is variable in accordance with the size and shape of the metal mould as determined in step
15 (b),
 - (d) thereafter releasing the upward pressure on the molten material in the direction of the mould such that it returns to the holding crucible to be reheated or maintained at a required temperature,
 - (e) thereafter removing the mould and continuing to cool the contents of the
20 mould remote from said casting station until the cast object has solidified, and thereafter removing the cast object from the mould, the process continuing with successive empty moulds being placed *in situ* at the casting station for further casting of required further objects.

2. A method according to Claim 1 in which step (b) includes calculating the required pressure and upward flow rate of molten material from the holding crucible into the mould with reference to a desired fill level rate or velocity within the mould which is constant to within $\pm 20\%$, preferably to within $\pm 10\%$, more preferably within $\pm 5\%$, irrespective of the shape or volume of the mould
5 occupied by the molten material, and step (c) includes carrying the pressure so that the fill level rate or velocity within the mould is constant to within $\pm 20\%$, preferably to within $\pm 10\%$, more preferably to within $\pm 5\%$.
3. A method according to Claim 2 in which step (b) includes calculating the
10 required pressure and upward flow rate of molten material from the holding crucible into the mould with reference to a substantially constant desired fill level rate or velocity within the mould, and step (c) includes varying the pressure so that the fill level rate or velocity within the mould is substantially constant.
4. A method according to any of the claims 1 to 3 further including the steps
15 of calculating the desired freezing rate of the molten material within a thermal plug forming element mounted beneath the entrance to the metal mould, such that when the mould has filled with molten material the molten material in the thermal plug forming element solidifies *in situ* to form a frozen plug in that region.
- 20 5. A method according to claim 4 which is performed without a gate adjacent the metal mould for controlling the flow of molten material into the metal mould, and wherein the flow of molten material into and out of the metal mould during step (c) is prevented by the formation of the frozen plug.

6. A method according to any preceding claim in which the metal mould is formed from aluminium or an aluminium alloy, preferably an aluminium bronze.

7. A process according to any previous claim further characterised in that molten material is injected into the mould cavity through a ceramic feed tube acting as a conduit between the molten material to be injected and the inside of the mould, the molten material being forced along the feed tube and into the mould cavity under pressure, such as gas pressure.

8. A process according to any preceding claim further characterised in that upstream of the casting process feed material, such as metal and metal additives, are first melted in a melting furnace within air or an inert atmosphere, such as argon, whereafter the molten material is transferred to a holding crucible substantially without exposure to air and delivered into the mould cavity under pressure at a constant fill rate to thereby minimise the presence of gaseous inclusions within the molten material in the mould as it freezes.

9. A process according to claim 8 further characterised in that molten material from the melting furnace is transferred to the holding crucible via a siphon tube arrangement in which molten material is initially transferred under pressure up the tube by an amount in excess to the height of the surface of the molten material before thereafter flowing under suction down a further part of the tube parallel to but remote from the inlet end of the tube to thereafter be delivered to the holding or crucible substantially without exposure to air.

10. Low pressure casting apparatus for performing a method according to claim 1, the apparatus including:

a metal mould;

a casting station;

a holding crucible for holding a charge of a molten material;

a conducting arrangement acting as a conduit for the molten material from the crucible to the metal mould; and

5 pressure producing means for controllably applying a pressure to the molten material in the crucible which causes the molten material to be transported along the conducting arrangement to the metal mould; and

a control arrangement for controllably varying said pressure in accordance with the size and shape of the metal mould.

10 11. A method of planning and controlling the low pressure casting of an object in a metal mould at a casting station, including the steps of:

calculating the desired freezing rate of a molten material which the object is to be formed from within a thermal plug forming element mounted beneath an entrance to the metal mould, such that when the mould has filled with molten
15 material the molten material in the thermal plug forming element solidifies *in situ* to form a frozen plug in that region, and

performing a low pressure casting operation without a gate adjacent the metal mould for controlling the flow of molten material into the metal mould, wherein the flow of molten material into and out of the metal mould after filling of
20 same is prevented by the formation of the frozen plug.

12. Low pressure casting apparatus for performing a method according to claim 11, the apparatus including:

a metal mould;

a casting station;

a holding crucible for holding a charge of a molten material;

a conducting arrangement acting as a conduit for the molten material from the crucible to the metal mould; and

5 pressure producing means for controllably applying a pressure to the molten material in the crucible which causes the molten material to be transported along the conducting arrangement to the metal mould;

10 in which the conducting arrangement does not include a gate adjacent the metal mould, but includes the thermal plug forming element mounted beneath an entrance to the metal mould which enables molten material to solidify *in situ* to form a frozen plug in that region thereby preventing the flow of further molten material into the metal mould.

13. Pressure casting apparatus including a pressure vessel, a heatable crucible having a heating arrangement, the crucible and heating arrangement being disposed within the pressure vessel for receiving a charge of material and heating or maintaining the charge to or at a casting temperature, transfer tube means between the inside of the crucible and the outside of the pressure vessel at a mould receiving casting station, means for introducing gas under pressure into the pressure vessel to thereby force molten material along the transfer tube to a mould at the mould receiving casting station when mounted thereon, and 20 means to reduce the gas pressure when the mould has been filled and closed to thereby permit it to be removed without leakage thereafter of molten material from the outlet end of the transfer tube.

14. Pressure casting apparatus according to Claim 13 in which the heating arrangement is an induction heating arrangement.

15. Apparatus according to Claim 13 or Claim 14 further characterised in that the pressure vessel includes a closeable lid above the crucible, the mould receiving casting station is on the outside of the lid and the transfer tube is substantially upright, in use.

5 16. Apparatus for closing a mould when filled with molten material, including a thermal plug forming element comprising a plug forming metal plate with an aperture through which molten material is forced under pressure from an inlet end to an outlet end adjacent the mould to be filled, the size and composition of the plate and aperture being chosen to ensure that when the mould has been
10 filled with molten material it thereafter solidifies in the aperture to form a frozen plug independent of solidification of the material within the mould.

17. Apparatus according to Claim 16 further characterised in that an apertured molten material impact-resisting plate is disposed around the inlet end of the plug forming metal plate to thereby protect the plug forming metal plate
15 from initial impact of a pressurised charge of molten material for filling the mould.

18. Apparatus according to Claim 17 further characterised in that the impact-resisting plate is made from a harder material than that of the plug forming metal plate.

19. Apparatus according to Claim 18 further characterised in that the impact-
20 resisting plate is made of an aluminium bronze.

20. Apparatus according to any one of Claims 16 to 18 further characterised in that the plug forming metal plate is made of aluminium.

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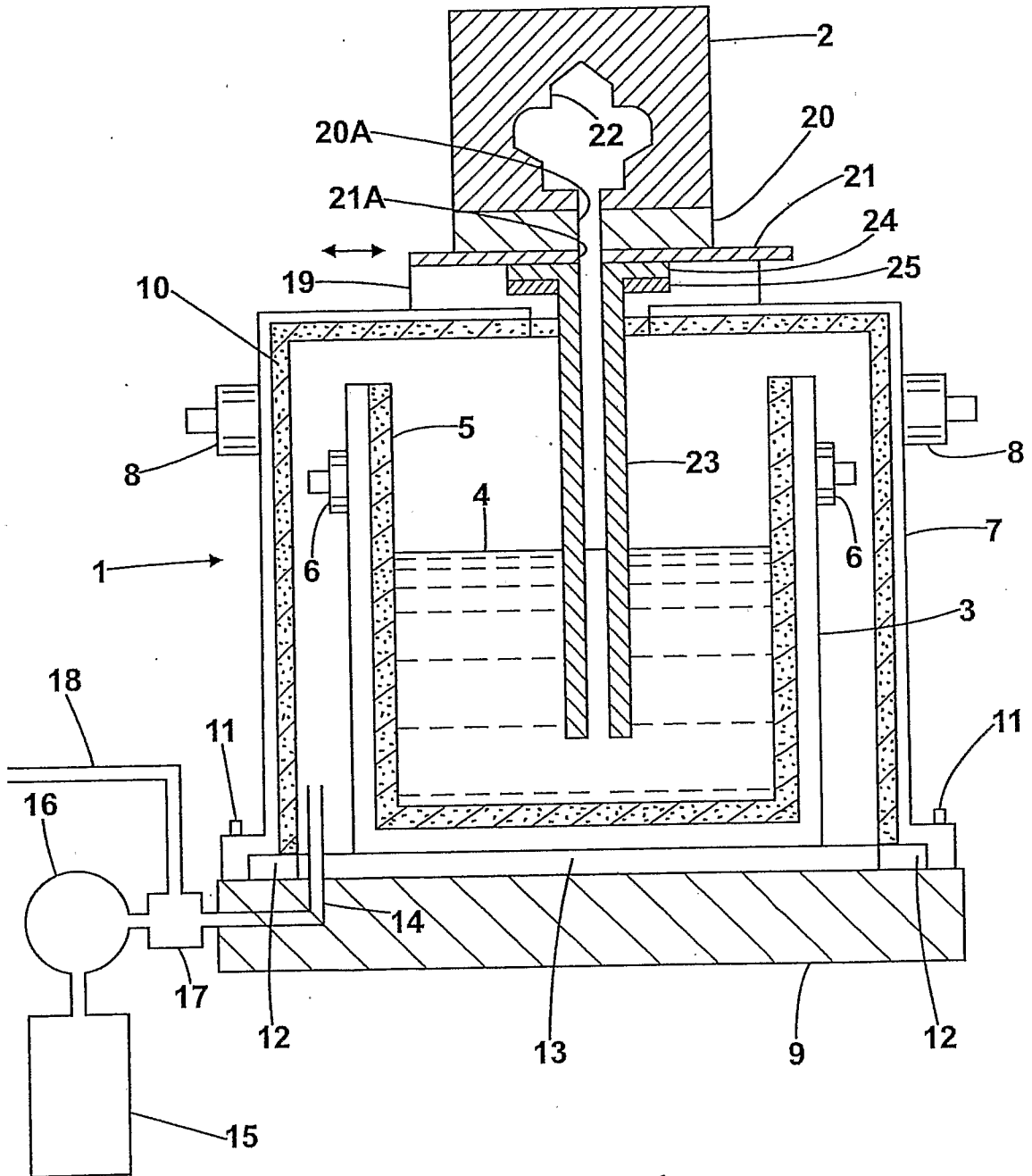


Fig. 1

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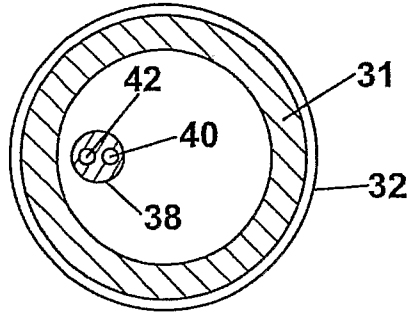


Fig. 3

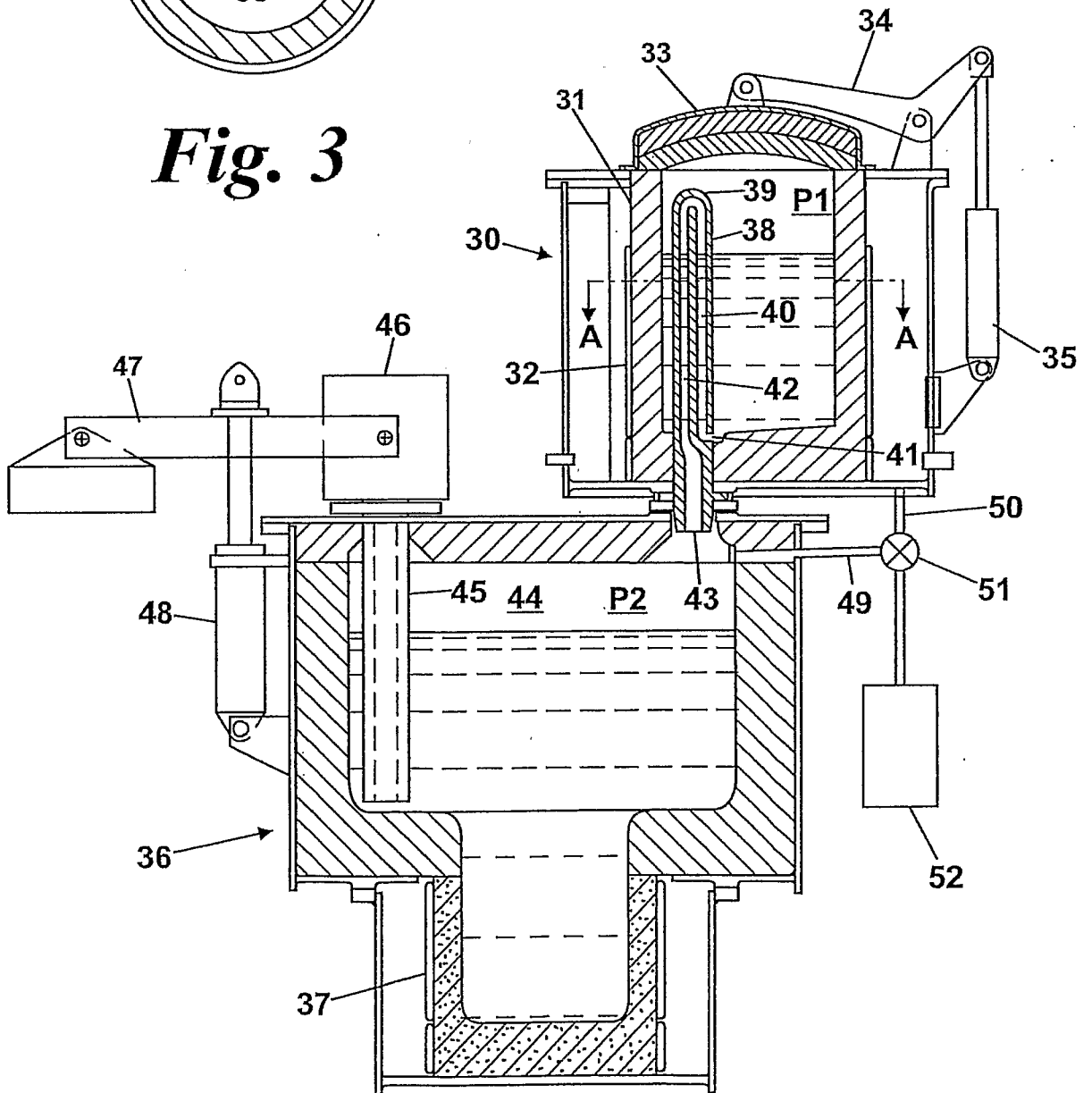


Fig. 2

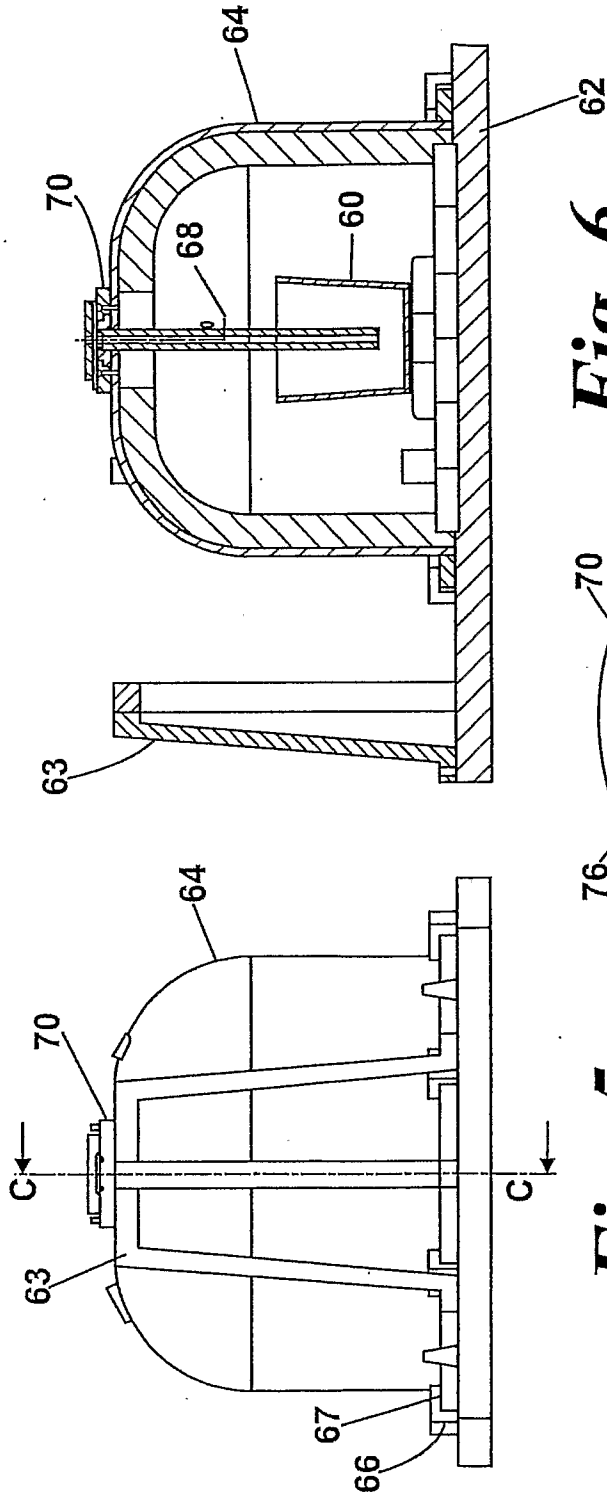


Fig. 6

Fig. 5

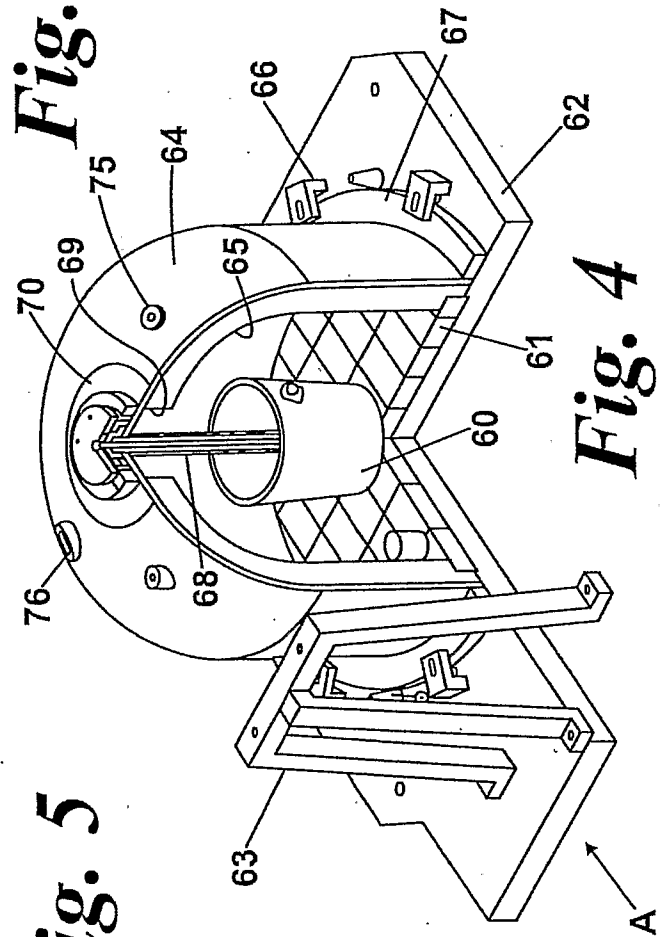


Fig. 4

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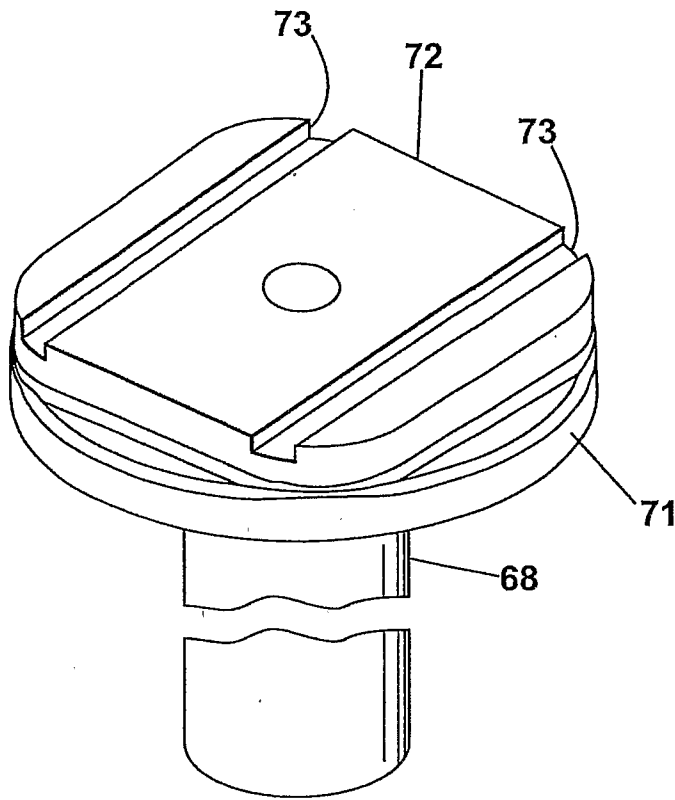


Fig. 7

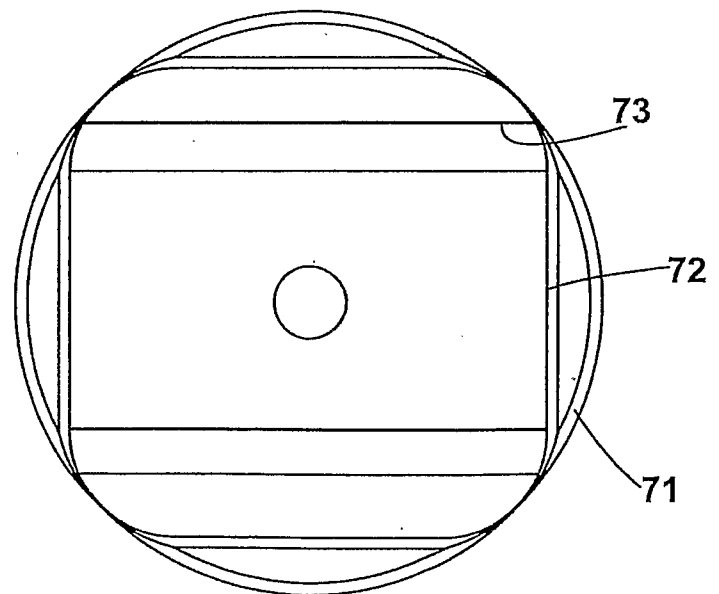


Fig. 8

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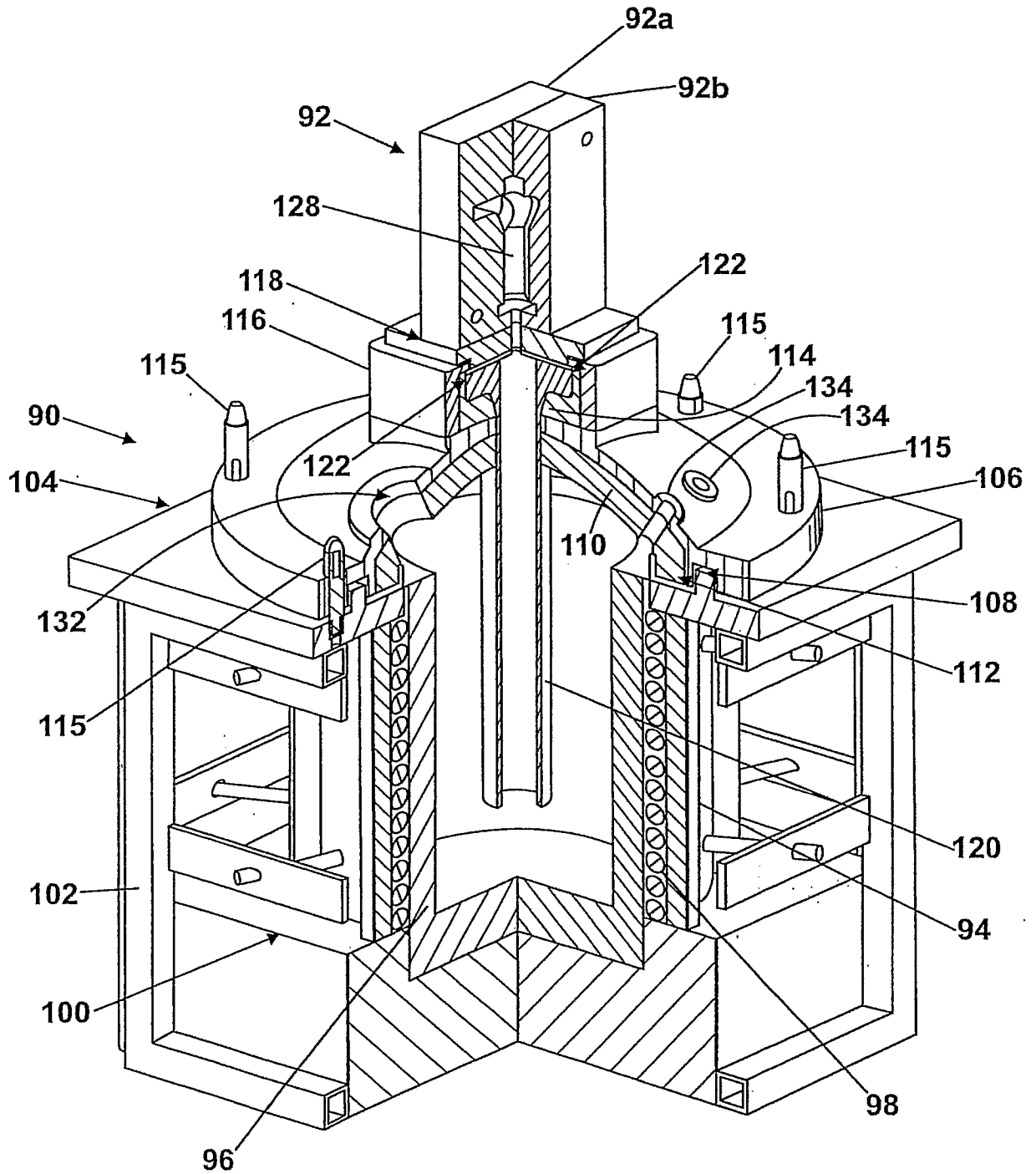


Fig. 9

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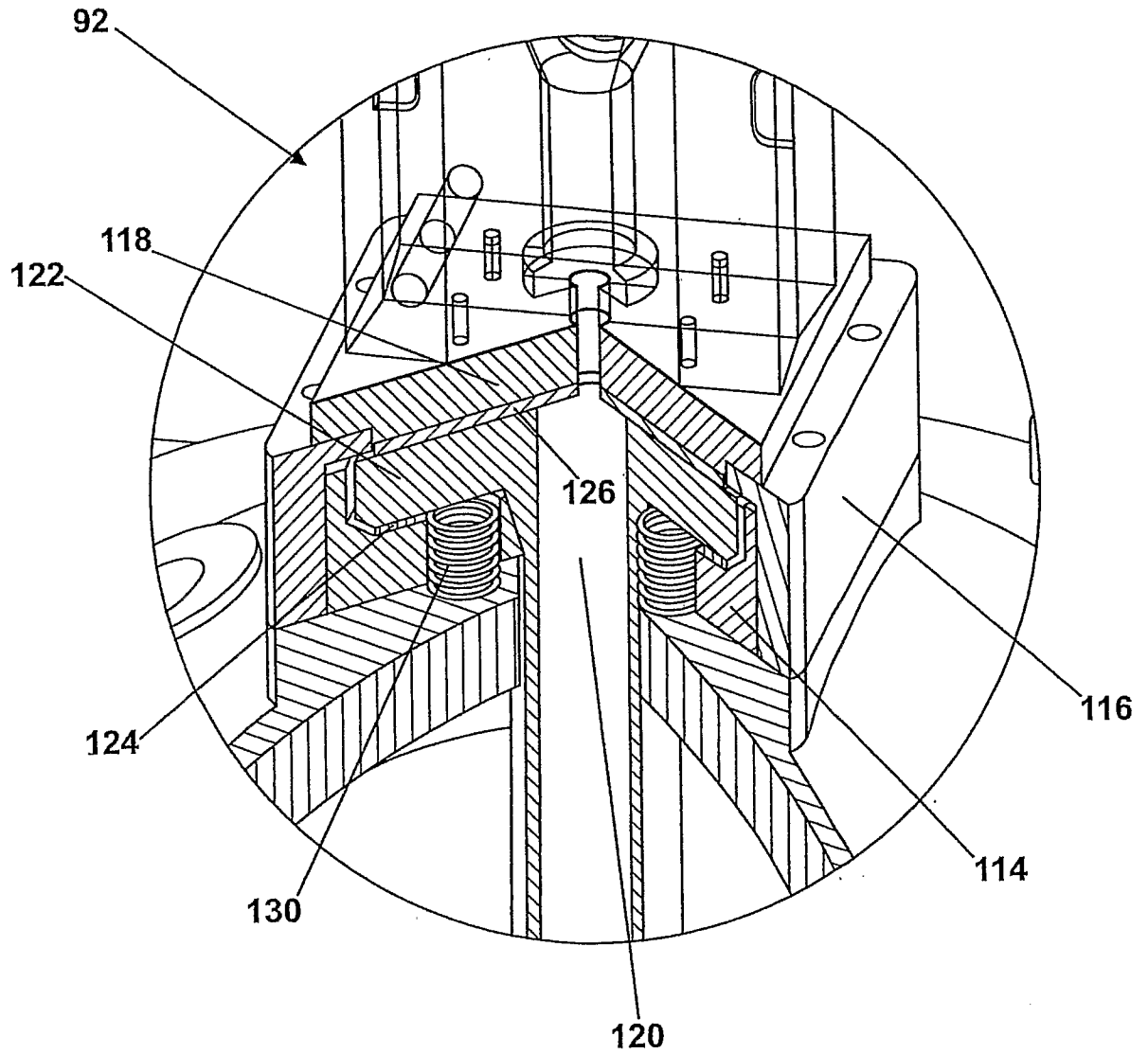


Fig. 10