CASTING PROCESS AND APPARATUS

Applicant: UNITED TECHNOLOGIES CORPORATION, Hartford, CT (US)

Inventor: Mark A. White, Port St. Lucie, FL (US)

Assignee: UNITED TECHNOLOGIES CORPORATION, Hartford, CT (US)

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ABSTRACT

A casting method includes coupling a mold to a crucible, the mold having one or more part-defining cavities and one or more feed passageways. A first rotating of the crucible and mold pours molten metal from the crucible through the one or more feed passageways into the one or more part-defining cavities. A second rotating of the crucible and mold returns molten metal from the one or more feed passageways, while leaving the part-defining cavities filled.
CASTING PROCESS AND APPARATUS

BACKGROUND

[0001] The disclosure relates to casting. More particularly, the disclosure relates to casting of superalloy components.

[0002] One form of investment casting is known as rollover casting. In rollover casting, a mold is mounted on a rollover crucible. The crucible contains molten metal. In an initial orientation, the mold opening faces downward and is melted to an upward-facing opening of the crucible. The crucible and mold are then rotated by 180° about a transverse axis so that the mold opening faces upward. This rotation causes molten metal from the crucible to pour into the mold, filling part defining cavities in the mold.

[0003] In certain forms, the molten metal may pass through a pour cone and downsprue and gate prior to reaching the mold cavity. Upon filling the mold cavity, excess material may pass up through a riser. The molten metal may be allowed to solidify in the crucible and the crucible rotated back to its initial orientation. The mold may be separated from the crucible before or after. The crucible may be charged with a fresh ingot of metal which is allowed to melt. A fresh mold may be mounted to the crucible and the process repeated.

[0004] The removed mold may be broken up. Solidified metal left in the pour cone, downsprue(s), gate(s) and riser(s) may be cut away from the cast parts and recycled. However, the recycling price is lower than the purchase cost. Thus, this represents only a partial recovery of value.

SUMMARY

[0005] One aspect of the disclosure involves a casting method including coupling a mold to a crucible, the mold having one or more part-defining cavities and one or more feed passageways. A first rotating of the crucible and mold pours molten metal from the crucible through the one or more feed passageways into the one or more part-defining cavities. A second rotating of the crucible and mold returns molten metal from the one or more feed passageways, while leaving the part-defining cavities filled.

[0006] In one or more further embodiments of the foregoing embodiments, the one or more feed passageways comprise a pour cone; and at least one downsprue between the pour cone and the part-defining cavities.

[0007] In one or more further embodiments of the foregoing embodiments, the second rotating returns said molten metal from the pour cone.

[0008] In one or more further embodiments of the foregoing embodiments, the second rotating returns said molten metal from the downsprue.

[0009] In one or more further embodiments of the foregoing embodiments, prior to the second rotating, metal at a lower part of the downsprue solidifies so that only a portion of metal from an upper part of the downsprue is returned.

[0010] In one or more further embodiments of the foregoing embodiments, there is a single downsprue to which a plurality of said part-defining cavities are coupled by gates.

[0011] In one or more further embodiments of the foregoing embodiments, the plurality of said part-defining cavities are arranged in a plurality of vertically-arrayed groups.

[0012] In one or more further embodiments of the foregoing embodiments: the process is repeated with the same crucible and a series of molds; and at least a portion of the returned metal from one mold is poured into the next said mold.

[0013] In one or more further embodiments of the foregoing embodiments, the method further comprises charging the crucible with additional metal prior to the pouring into the next said mold.

[0014] In one or more further embodiments of the foregoing embodiments, the charging comprises introducing 10-50% of metal mass poured.

[0015] In one or more further embodiments of the foregoing embodiments, the return is of 10-50% of metal mass poured.

[0016] In one or more further embodiments of the foregoing embodiments, the return is after metal in the part-defining cavities has solidified.

[0017] In one or more further embodiments of the foregoing embodiments, the metal is a nickel-based superalloy or a cobalt-based superalloy.

[0018] In one or more further embodiments of the foregoing embodiments, the part-defining cavities cast gas turbine engine components.

[0019] Another aspect of the disclosure involves a casting apparatus comprising: a base; a crucible having an interior and a pour opening; an actuator coupling the crucible to the base to articulate the crucible between a first orientation and a second orientation; and a controller. The controller is configured to operate the actuator to articulate the crucible from the first orientation to the second orientation to pour molten metal from the crucible interior through the pour opening and into a mold and return the crucible to the first orientation before all the poured metal has solidified.

[0020] Another aspect of the disclosure involves a casting mold comprising: at least one port for introducing molten metal; at least one part-defining cavity in communication with the port; and one or more passageways between the at least one part-defining cavity and the port. The one or more passageways includes a gate having a localized reduction in cross-sectional area of at least 30%.

[0021] In one or more further embodiments of the foregoing embodiments, the mold comprises: a main ceramic body along the part-defining cavity, and one or more passageways; and an additional layer of localized fibrous ceramic insulation away from the part-defining cavity.

[0022] In one or more further embodiments of the foregoing embodiments, the reduction is at least 50%.

[0023] In one or more further embodiments of the foregoing embodiments, the additional layer is at most partially along the gate.

[0024] The details of one or more embodiments are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] FIG. 1 is a semi-schematic vertical sectional/cutaway view of a casting apparatus.

[0026] FIG. 1A is an enlarged view of a single part cavity of a shell of the casting apparatus of FIG. 1.

[0027] FIG. 2 is a view of the apparatus of FIG. 1 in an inverted condition/orientation.

[0028] FIG. 3 is a view of the apparatus after pour-back.

[0029] Like reference numbers and designations in the various drawings indicate like elements.
FIG. 1 shows a furnace 20 having a crucible 22 for melting and containing molten metal. The crucible has an interior 24 extending to a pour opening 26 for pouring the metal 28. The exemplary opening 26 is at the top of the crucible in the FIG. 1 orientation. The exemplary crucible defines a central longitudinal axis 500 which, in the FIG. 1 orientation, may be parallel to a vertical direction 502.

The exemplary furnace includes means 30 for heating the metal 28 in the crucible. Exemplary means are an induction coil (e.g., water-cooled) and associated powering circuitry.

The exemplary furnace 20 is a roller furnace wherein a portion 38 of the furnace including the crucible is mounted by a pivot 40 for rotation relative to a base portion 41 about a transverse (e.g., horizontal) axis 504. An actuator 42 may be provided to rotate the furnace portion 38 about the pivot 40 and axis 504. The exemplary actuator comprises a conventional stepper motor although hydraulic or pneumatic actuators are also possible.

As is discussed further below, the crucible may rotate at least to a pouring orientation. The exemplary rotation may be to an orientation such as shown in FIG. 2 and discussed further below. The exemplary rotation is shown as 180° rotation about a horizontal axis. Alternative rotations might be of greater or lesser amount but would be expected to be somewhere between 90° and 270°, more narrowly, between 135° and 225° or between 150° and 210°.

As is discussed further below, the crucible may be mated to a consumable/disposable casting mold 50. The furnace may be provided with means for interfacing with the mold. The exemplary means for interfacing both mechanically couples the mold to the portion 38 to allow the mold to rotate with the portion 38 and provides a seal to permit pouring of molten metal from the crucible into the mold. The exemplary means comprises a ceramic seal 60 positioned with a perimeter portion of its underside 62 mating with a rim 64 of the crucible. The seal comprises an inboard port or aperture 66 between the underside 62 and an upper surface 68. An inboard portion of the upper surface 64 mates with a rim 70 of the mold. The means further includes a pivoting (or otherwise engagable/dissengagable) mold clamp 72 which may be positioned to axially and transversely retain the mold to the seal and crucible. Additional routine manufacturing details common to roller furnaces are omitted for ease of illustration.

For ease of reference, two orientations (FIG. 1 and FIG. 2) can be respectively identified as an upright orientation and an inverted orientation. The articulation between these orientations is identified as consisting only of a rotation about a fixed horizontal axis 504. This is exemplary. Other rotations and movements may be involved. For example, one or more different steps identified as being performed in one or two specific orientations may be performed in a slightly different orientation. Some steps will occur over a range of orientation. Thus, any identification herein that a step occurs in a particular orientation (except when explicitly identified as requiring a single orientation) does not mean that the step occurs while the apparatus is non-moving. For example, in the absence of use of a valve or removable plug, pouring will occur over a range of orientations during the rotation.

The mold 50 includes an interior formed by one or more part cavities 80 (FIG. 1) for casting the individual parts. Exemplary parts are gas turbine engine components such as blades, vanes, combustor panels, and blade outer air seals. These exemplary components may be cast of an alloy such as a nickel-based superalloy or a cobalt-based superalloy.

Beyond the part cavities 80, the mold may include passageways for delivering molten metal to the part cavities and evacuating air and/or molten metal from the part cavities. For example, one or more pour cones 82 may be formed to receive molten metal. These one or more pour cones may communicate with the part cavities via a downspout 84 passageway extending downward in the mold (when viewed in the pouring condition) and coupled to the part cavities by gates 86. Risers (not shown) or other passageways may extend upward from the part cavities to evacuate air and/or metal. For example, the riser may have an opening (not shown) at or near the top of the mold. The appearance of molten metal rising in the riser to near the opening may confirm filling of the part cavity.

The exemplary implementation has a single central pour cone 82 and a single central downspout 84 associated therewith. Alternative implementations may have multiple pour cones and/or associate multiple downspouts with a given pour cone. The exemplary mold associates multiple part cavities 80 with a given downspout. In this example, each part cavity has an associated gate 86 coupling the part cavity to the downspout. The exemplary part cavities are grouped as a plurality of vertical arrays along a length (height) of the downspout. In this example, there are four such arrays at 90° angles about the downspout.

As is discussed further below, the exemplary gate includes a restriction/constriction 100 defining a narrowing in the molten metal flowpath to the associated part cavity. As is discussed further below, the restriction creates an enhanced local surface exposure of the molten metal in the gate to the shell material. This may enhance cooling at the gate relative to cooling in the downspout. Accordingly, the molten metal may solidify in the gate prior to solidifying in the downspout. As is discussed further below, this facilitates a returning to the upright condition prior to metal solidification in the downspout, thereby allowing recovery of metal from the downspout. At the constriction 100, exemplary cross-sectional flow area is equal to or less than 70% of the cross-sectional areas of gate regions 102 and 104, respectively upstream of and downstream of the constriction (more narrowly, less than 50% or less than 40% or an exemplary 25-35%). The actual nature of the constriction may depend upon the geometry of the gate which may, in turn, depend upon the geometry of the part being cast. For circular cross-section gates, the constriction may be of circular planform formed by opposed frusto-conical surfaces. For more rectangular planform cross-section gates, the constriction may be formed by opposed triangular-section prisms.

The mold may be formed via conventional means such as applying a ceramic stucco (shelling) to sacrificial patterns (e.g., wax) dimensioned to form the part cavities and passageways. The overall pattern shelled may be a pattern assembly (e.g., of individual patterns associated with individual parts (optionally including their gates)) and one or more additional patterns for the passageways. These may be secured to each other such as via wax welding. Stucco application may be via a multi-stage dipping process. The mold (shell) may be allowed to dry and the wax may be removed such as via a steam autoclave de-wax. The shell may be further hardened via baking.
In this example, the furnace may be charged with metal prior to shell installation. With the furnace in its upright position, or optionally with the seal in place, one or more ingots may be introduced to the furnace (e.g., through the open top or the seal opening/aperture) and melted. The seal may be installed (if not already installed). The mold may be installed and secured via the clamp. With material sufficiently molten, the control system may cause the actuator to rotate the mold to the inverted condition and dwell for the desired time necessary for solidification of the metal, the part cavity, and/or gate and then return the furnace and mold to the upright orientation causing pour-back. With the furnace upright, the mold may be removed. The furnace may be recharged and a new mold put in place and the process repeated. The cast parts may be removed from the removed mold in one or more stages which may include mechanical and/or chemical removals. For example, an initial de-shelling may be largely mechanical breaking or cutting apart the shell. Chemical removal (e.g., alkaline and/or acid leaching) may be used and is particularly relevant in the case where the mold includes cores which become embedded in the castings (decoring). There may be trimming of gate material from the cast part. There also may be further machining of the cast part prior to additional treatments such as the application of a thermal barrier coating system or an erosion coating system.

The material cut away from the castings (but ignoring material along the castings which may later be machined away) may, in a prior art baseline, typically account for an exemplary about 65% (e.g., 50-70%) of the mass of poured metal. By allowing pour-back, this wastage may be reduced. For example, the metal returned to the crucible may represent at least 10% (e.g., 10-50%) of the initial pour, more narrowly, 20-40% or 25-35%. The returned metal may account for substantially the entirety of any metal in the pour cone upon initial pour (e.g., allowing for residual metal that has wet or otherwise adhered to the surface of the pour cone and typically at least 95%). The returned metal may also represent most of the metal from the downsprue (e.g., at least 50%, more particularly, at least 70%). It may represent some of the gate metal (e.g., 0-60%). For a given mass of pour Ms, the returned mass Mr reduces the required mass for re-charging the furnace. Thus, one or more ingots totaling a recharge mass Mrc may be used where Mrc is 50-90% of Mr, more narrowly, 60-80% or 65-75%.

In one specific example, the charge (Mj) is initially 75 pounds (34 kg) and the gates/castings are 40 pounds (18 kg) and the returning metal to the crucible Mj is 35 pounds (16 kg) resulting in 47% return to the crucible. This returning metal comes from the downsprue and pour cone. The process thus saves 47% metal and associated cost in this example and thereby presents the potential to save 35% to 60% in typical examples when used on varieties of castings.

Depending upon the particular part(s) being cast and the associated passageway configuration, the labor in removing the part(s) from the mold may be reduced relative to the baseline. For example, if there were no metal in the pour cone and downsprue, those portions of the mold might not need to be broken up. Additionally, if portions of the passageway(s) otherwise connecting separate parts are in the pour back region fewer cuts may be required to separate individual parts from each other. This can reduce labor costs.

As noted above, the process may be performed with otherwise conventional furnace and mold configurations. However, these may be modified or optimized for partial metal return. For example, the furnace may be modified relative to a baseline furnace by reprogramming a controller 120 (e.g., microcontroller, computer, or the like) to shorten the time the mold is inverted. Mechanical modifications may be made to provide quicker or more powerful actuators to speed the rotation. Other modifications might include increasing mechanical robustness of mold-engaging features if rotation speed is to be increased.

The mold might be modified relative to a baseline mold by enhanced cooling of portions of the passageways adjacent the metal that is to be solidified versus portions of the passageways from which it is desired the metal return. Similarly, enhanced insulation may be provided adjacent the portions from which return is desired. One example of this is adding the aforementioned gate constriction 100. In a re-engineering from a baseline, the restriction may be added to an existing pattern configuration. For example, the restriction may be formed by a notch or notches in the pattern portion corresponding to the gate. This, in turn, may be provided by adding a complementary protrusion to the mold in which the pattern (or the gate) is molded.

Also, FIG. 1A shows localized insulation 200 in the form of spun ceramic fiber wrapping (e.g., Mullite or kaolinite). Exemplary wrapping is available from Unitex L, LLC, Niagara Falls, New York, as FIBERFRAX DURABLEX IB-8. Such material is known for wrapping of investment casting molds for the purposes of guiding directional solidification to provide desired crystalline orientation. Thus, some prior art may provide a gradient of such insulation progressing from relatively low near the distal ends of the part cavities to relatively high at the pour cone. In addition to such existing use of insulation, an additional amount of insulation may be provided along the downsprue and pour cone to maintain melten the associated metal for yet a longer duration after the metal in the part cavity has solidified.

Accordingly, the exemplary insulation 200 is shown relative to a baseline lacking such fibrous ceramic insulation. This insulation is provided only along the pour cone, downsprue, and upstream portions of the gates and not along the part cavities. Such an amount of insulation may, however, be added in addition to existing fibrous ceramic insulation of a baseline. At some point after shelling, the additional localized insulation may be provided to allow melten metal in pour cone and downsprue to remain molten for a longer period of time after other metal has solidified. This may involve applying fibrous ceramic material 200 (e.g., batt or other blankets) in areas upstream of the constriction 100. This may be provided by wrapping pre-cut templated pieces of the blanket around the shell and securing via a ceramic adhesive.

Yet other modifications include providing increased mold robustness/strength (thickening, mechanical reinforcements or the like). This may be appropriate for two reasons. First is, if present, the increased speed and associated loads. Second is the absence of solidified metal in the pour cone and downsprue relative to the baseline. The shell may need increased robustness to carry loads that would have been carried by the solidified metal in the pour cone and downsprue.

One or more embodiments have been described. Nevertheless, it will be understood that various modifications may be made. For example, when implemented using a baseline furnace or modification thereof or a baseline mold or modification thereof or to make a given part, details of the baseline(s) or part may influence details of any particular
implementation. Accordingly, other embodiments are within the scope of the following claims.

1. A casting method comprising:
   coupling a mold to a crucible, the mold having:
   one or more feed passageways, each of the feed passageways in fluid communication with a constriction, the constriction forming a gate portion of the feed passageway located between an upstream portion and a downstream portion;
   one or more part defining cavities, each of the part defining cavities in fluid communication with one of the feed passageways via one of the constrictions;
   localized insulation arranged along the upstream portion of the one or more feed passageways; and
   an enhanced local surface exposure arranged along the downstream portion of the one or more feed passageways;

first rotating the crucible and mold to pour molten metal from the crucible through the one or more feed passageways into the one or more part-defining cavities; and
second rotating the crucible and mold to return molten metal from the one or more feed passageways, while leaving the part-defining cavities filled.

2. The method of claim 1 wherein the one or more feed passageways comprise:
   a pour cone; and
   at least one downsprue between the pour cone and the part-defining cavities.

3. The method of claim 2 wherein:
   the second rotating returns said molten metal from the pour cone.

4. The method of claim 3 wherein:
   the second rotating returns said molten metal from the downsprue and the upstream portion of the feed passageways.

5. The method of claim 2 wherein:
   prior to the second rotating, metal at a lower part of the downsprue solidifies so that only a portion of metal from an upper part of the downsprue is returned.

6. The method of claim 2 wherein:
   there is a single downsprue to which a plurality of said part-defining cavities are coupled by gates.

7. The method of claim 6 wherein:
   the plurality of said part-defining cavities are arranged in a plurality of vertically-arrayed groups.

8. The method of claim 1 wherein:
   the process is repeated with the same crucible and a series of molds; and
   at least a portion of the returned metal from one mold is poured into the next said mold.

9. The method of claim 8 further comprising:
   charging the crucible with additional metal prior to the pouring into the next said mold.

10. The method of claim 9 wherein charging the crucible comprises introducing 10-50% of the metal mass poured.

11. The method of claim 1 wherein:
   the return is of 10-50% of metal mass poured.

12. The method of claim 1 wherein:
   the return is after metal in the part-defining cavities has solidified.

13. The method of claim 1 wherein:
   the metal is a nickel-based superalloy or a cobalt-based superalloy.

14. The method of claim 1 wherein:
   the part-defining cavities cast gas turbine engine components.

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20. The method of claim 1 wherein the localized insulation is a fibrous ceramic material.

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