(54) Title: PROCESS FOR CASTING A SEMI-SOLID METAL ALLOY

(57) Abstract: A method of forming a metal part includes heating a metal alloy composition to form a liquid that is substantially free of metal solids. The liquid is cooled to form a semi-solid metal alloy slurry having a low weight percentage of substantially non-dendritic solids. The semi-solid metal alloy slurry is transferred to a mold at a low pressure and is cooled to cast a substantially solid part.

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PROCESS FOR CASTING A SEMI-SOLID METAL ALLOY
CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of United States Provisional Application No. 60/527,030, filed on December 4, 2003, the entire contents of which are incorporated by reference.

BACKGROUND OF THE INVENTION

[0002] This invention relates to industrial metal forming, and more particularly to a process for forming metal components from non-dendritic, semi-solid metal slurries.

[0003] It is well known that when a molten metal alloy is transferred into a mold to create a part, the metal undergoes a phase change from liquid to solid. The metal density changes during this phase change, resulting in a change in volume. For most metals, the density increases during freezing, resulting in a loss in volume. In casting, this loss of volume creates a casting defect known as shrinkage. Casting molds are designed so that the part freezes in a directional manner that allows for molten metal to fill into the voids created by the loss of volume. This step of compensating for shrinkage is known as "feeding."

[0004] Molten alloy will continue to flow even after it begins to solidify. Under normal solidification conditions, the solid phase will possess a morphology that is referred to as dendritic. Dendritic means that the solid phase has a tree-like structure, with branches and side arms of solid protruding into the liquid. Dendrites have a large surface area to volume ratio. As the metal freezes, the dendrites occupy a larger volume fraction of the alloy, and at some point the dendrites form a network that prevents the partially solidified alloy from easily flowing. The partially solidified alloy cannot feed shrinkage when this occurs. The amount of solid present in the alloy when the metal ceases to flow and accommodate shrinkage is known as the coherency fraction solid. The coherency fraction solid will occur at varying fraction solids depending on the morphology of the freezing alloy. The coherency fraction solid is relatively low, usually about 0.20 fraction solid; as a result, normal casting processes use molten alloy that is superheated as much as 100°C above the liquidus temperature. This extra heat allows the alloy to remain molten for a longer period of time to allow for feeding of the shrinkage. A result of the energy used to heat the alloy to higher temperatures is an increase in associated cycle time due to the extra heat that must be removed through the
casting process during part formation, and die life is reduced by the increased thermal shock on the tool.

[0005] Existing semi-solid casting processes rely upon controlling the morphology of the solid phase so that the solid phase possesses a globular, spheroidal or ellipsoidal shape. Specifically, it has been discovered that various processing and physical property advantages can be achieved by casting or otherwise forming metal components from a non-dendritic, semi-solid metal slurry. This allows for easier movement of the solid phase as it freezes because of the prevention of the formation of a dendritic network. The non-dendritic metal particles in the semi-solid slurry provide substantially reduced viscosity for a given solids fraction as compared with a semi-solid metal alloy composition containing dendritic particles. Often the difference in viscosity is several orders of magnitude. Feeding of shrinkage is easier to accommodate with a globular, non-dendritic morphology. Heretofore, the majority of semi-solid processes use a high pressure injection system to force the semi-solid alloy into an associated mold.

[0006] When molten alloy is held at a temperature right at or slightly above the liquidus, copious nucleation of solid particles form within the melt as the metal is transferred into the mold. The resulting solid particles are very small and finely dispersed, such that, as the metal freezes in the mold, the metal continues to flow and feed because the dendrites are generally more round. Feeding shrinkage is enhanced by this process.

[0007] There are deficiencies to using this process. For example, maintaining the molten alloy at a temperature just above the liquidus is challenging from an industrial standpoint because of furnace temperature fluctuations. Furnaces are normally filled with molten metal periodically either through a central feeding system or from a crucible. This molten alloy is superheated above the liquidus to prevent the metal from beginning to freeze in the metal transfer system. When the new metal is added to the holding furnace the resultant metal temperature is normally well above the liquidus such that it is impossible to utilize the aforementioned process. Further, the solid particles are very small and dispersed within the liquid, but they are still dendritic in shape. Formation of round particles from fine dendrites requires time to allow for a reduction in surface area of the particles. The fine dendrites created by low-temperature pouring enhances feeding compared with liquid casting processes, but the advantages that are possible using globular particles are not fully realized in existing processes.
More recent processes have utilized molten metal that has been modified with "grain refiners." Grain refiners are added to a molten metal to promote copious nucleation of the solid phase so that the morphology becomes non-dendritic and globular in a short amount of time. The time required to allow the dendrites to coarsen into round particles makes grain refiners challenging to use in industrial processes. In an industrial process, the melt would need to be cooled and held at a temperature that allows the solid particles to coarsen into round particles.

Non-dendritic, semi-solid slurries with fractions solid above approximately 0.4, i.e., high fraction solid slurries, possess solid-like properties in the unsheared state because of the shear-dependent viscosity of the slurry (e.g., the slurry can support its own weight for finite amounts of time). The slurry is typically injected into a mold via a high-pressure casting machine with injection forces adequate to create enough shear to decrease the viscosity of the slurry and enable filling of a mold cavity. Typically, the high-pressure casting machines utilize injection forces of greater than 1000 psi, and at least greater than 500 psi. Because shear is necessary to initiate flow, high-pressure injection style casting machines (injection molding, die casting, or squeeze casting machines) have been utilized to cast semi-solid slurries having fractions solid above about 0.4.

Semi-solid slurries at low fractions of solid (about less than 0.20) do not have enough viscosity or strength to support their own weight. Heretofore, low fraction solid slurries were not widely used in high pressure industrial casting until recently for a number of reasons. First, it was believed that the transfer of low fraction solid slurries to a relatively cold vessel (e.g., the mold or cold chamber) would return the microstructure of the slurry to a dendritic state. Flow of the slurry into the mold would thus cease at fractions solid much lower than a high fraction solid slurry. Secondly, the low-fraction solid slurry has more heat than high fraction solid slurries, so the full benefits of using semi-solid rather than liquid casting could not be realized. For example, die life and casting cycle time would not be expected to improve as drastically as with a high fraction solid slurry. Finally, existing semi-solid processes were not designed to create low-fraction solid slurry that was suitable for casting. Equipment was designed to handle the more solid-like material, not the lower viscosity, low fraction solid slurry.
Recent work with low-fraction semi-solid slurries has shown the slurry will remain essentially non-dendritic throughout the filling of the mold during high-pressure molding processes. High-pressure casting machines now cast low-fraction solid slurry and gain many of the benefits of semi-solid processing, such as reduced cycle time, increased mold life, and increased casting mechanical properties. Furthermore, major changes that were necessary to the casting equipment to use high-fraction solid slurry are no longer necessary.

Many existing liquid alloy (i.e., no solids) casting processes do not use high-pressure injection. These low pressure processes include sand casting, gravity or low-pressure permanent mold, investment casting, and lost foam casting. These processes each have unique advantages for the production of certain castings compared with high pressure casting processes. Complex shapes can be produced with sand and lost foam casting because molds associated with these processes are not limited in geometry. Tooling costs are lower and make casting of low-volumes of parts more economical. Casting equipment is less expensive compared with high-pressure casting processes. Current automotive parts produced with these processes include closed-deck internal combustion engines, intake manifolds, pistons and wheels. In these processes, the molten metal fill velocity is much slower than high pressure casting processes. Therefore, to allow filling of the entire mold, the wall thickness of the cast components is usually thicker than a comparable high pressure casting to ensure the alloy does not solidify prior to flowing into the walls. However, there are disadvantages to low-pressure molding techniques. For example, the amount of time necessary to remove heat from the molten metal is correspondingly longer than in high pressure processes.

Use of low pressure processes for production of castings has been limited because of the relatively long cycle, in particular the long "dwell time" relative to high-pressure casting processes.

Another problem with low pressure casting processes is the lower mechanical strength of the castings compared with high pressure castings. Mechanical strength for a given alloy is inversely correlated to the grain size of the solidified casting. Grain size is directly related to the cooling rate of the metal within the casting.

SUMMARY OF THE INVENTION

One aspect of the present invention is a method of forming a metal part. The method includes heating a metal alloy to form a liquid that is substantially free of metal
solids. The liquid is cooled to form a semi-solid metal alloy slurry having a weight percentage of solids in the range of about one percent to about thirty percent, and wherein the slurry is substantially free of dendritic solids. The semi-solid metal alloy slurry is transferred to a mold at a low pressure, and the metal alloy slurry is to cast a substantially solid part.

[0016] Another aspect of the present invention is a method of casting metallic parts. The method includes forming a semi-solid metal alloy slurry including globular solids. The semi-solid metal alloy slurry is substantially free of dendritic solids. The metal alloy slurry is transferred to a mold having a sprue and runner connected to a mold cavity, and the metal alloy slurry flows through the sprue and runner into the mold cavity. The metal alloy is cooled in the mold cavity to substantially solidify the metal alloy and form a part. The metal alloy is pressurized in the mold cavity at a pressure of about one hundred pounds per square inch or less during cooling of the metal alloy.

[0017] Another aspect of the present invention is a system for making cast metallic parts. The system includes a furnace having a heated vessel suitable for holding liquid metal alloy. The system also includes a semi-solid slurry production machine having a movable agitating member configured to agitate metal alloy to produce a semi-solid metal alloy slurry having a weight percentage of non-dendritic solids of about one percent to about twenty percent. The system further includes a mold having a mold cavity and an intake runner and a vent connected to the mold cavity. A metal transfer device transfers semi-solid metal alloy slurry from the semi-solid slurry production machine to the mold.

[0018] These and other features, advantages, and objects of the present invention will be further understood and appreciated by those skilled in the art by reference to the following specification, claims, and appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] Fig. 1 is a schematic top plan view of a system for making cast metallic parts according to one aspect of the present invention; and

[0020] Fig. 2 is a partially schematic view of a mold of the system of Fig. 1.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

[0021] For purposes of description herein, the terms "upper," "lower," "right," "left," "rear," "front," "vertical," "horizontal," and derivatives thereof shall relate to the invention as oriented in Figs. 1 and 2. However, it is to be understood that the
invention may assume various alternative orientations and step sequences, except where expressly specified to the contrary. It is also to be understood that the specific devices and processes illustrated in the attached drawings and described in the following specification are simply exemplary embodiments of the inventive concepts defined in the appended claims. Hence, specific dimensions and other physical characteristics relating to the embodiments disclosed herein are not to be considered as limiting, unless the claims expressly state otherwise.

[0022] The benefits of non-dendritic semi-solid forming include higher speed part forming, high speed continuous casting, lower mold erosion, lower energy consumption, improved mold filling, reduced oxides for improved machinability of the finished metal components, and less gas entrapment resulting in reduced porosity. Other advantages of casting or otherwise forming metal components from a semi-solid slurry includes less shrinkage during forming of the metal components, i.e., near-net-shape castings, fewer voids and lower porosity in the formed metal components, less macrosegregation, less susceptibility to hot tearing, and more uniform mechanical properties (e.g., strength). It is also possible to form more intricate parts using non-dendritic, semi-solid alloy compositions during casting or other forming techniques. For example, parts having thinner walls with improved strength properties are possible.

[0023] The present invention provides an improved process for utilizing low-fraction solid slurry with a non-high pressure injection casting process. More specifically, the present invention provides a method of utilizing low-fraction solid slurries with non-high pressure casting processes that result in a decrease of process cycle times by as much as 50%. Also, the decreased heat of semi-solid slurries in low pressure casting processes decreases the grain size and improves mechanical properties of the castings.

[0024] As utilized herein, the low-fraction solid slurry refers to a semi-solid slurry having a sufficiently low weight fraction of non-dendritic solids so that the semi-solid slurry readily flows in a viscous manner with little or no applied shear stresses. Conversely, high-fraction solid slurry requires a finite applied shear stress to initiate viscous flow. Over time, a high-fraction solid slurry will flow without applied shear stress (i.e., as a result of its own weight); however, a relatively long duration of time is required to achieve viscous flow, and the amount of viscous flow achieved after the long duration of time is negligible. Further, the long duration of time required to achieve the viscous flow is significantly greater than cycle times desired in industrial metal casting
and forming processes. The low-fraction solid slurry can achieve viscous flow in a
duration of time suitable for industrial metal casting and forming processes and without
any applied shear stresses, and the viscous flow can be enhanced by application of low
pressure, as will be described in further detail hereinafter. Suitable weight percentages
of non-dendritic solids will depend upon variables such as the alloy composition, mold
configuration, and other such process variables. In general, the preferred weight
percentage of non-dendritic solids will be in the range of about one to twenty, and more
preferably in the range of about five to fifteen. However, somewhat higher weight
percentages of solids up to thirty or thirty-five percent may be utilized in some
applications. A description of forming and processing rheocast structures is given in
Institute of Technology, by co-inventor Raul A. Martinez-Ayers, published September
2004, the entire contents of which are incorporated by reference. The weight
percentage of solids in the low-fraction solid slurry is sufficient to permit casting
utilizing non-high pressure injection casting processes (low-pressure casting methods)
that utilize pressures that are substantially less than die casting or the like.

Examples of the low-pressure casting methods include sand casting, gravity or
low-pressure permanent mold, investment casting, and lost foam casting. However,
other low-pressure methods be also be utilized for a particular application. Such low-
pressure casting methods generally utilize pressures in the range of atmospheric pressure
to about one hundred pounds per square inch (psi), but can utilize pressures as high as
500 psi, or as low as 0.1 psi, depending upon the requirements of a particular
application.

A process according to one aspect of the present invention utilizes a low-fraction
solid slurry with a low pressure injection casting process. Fig. 1 is a partially schematic
plan view of a casting system 1 according to another aspect of the present invention. A
furnace 2 holds molten metal alloy 4 at a temperature above its liquidus temperature.
The furnace 2 is a commercially available unit that includes a vessel 5 forming a dip
well providing access to the molten metal alloy 4. A robot 10 or other such
commercially available transfer device includes a movable vessel 11 or the like for
transferring the molten metal alloy 4 from the furnace 2 to a semi-solid slurry
production machine 3. Various slurry production machines and processes have been
developed. One example of a semi-solid slurry production machine and method is
disclosed in U.S. Patent No. 6,645,323, the entire contents of which are incorporated by reference. The metal alloy is agitated and cooled in the semi-solid slurry production machine 3 to produce a slurry having non-dendritic solids that approach a spherical configuration. The robot 10 transfers the slurry 12 to a mold 13. The slurry 12 has a weight fraction solid content preferably of from about one percent to about twenty percent at the instant the slurry 12 is transferred to the mold 13, and more preferably of from about five percent to about ten percent. A plurality of molds 13 may be mounted on a rotatable table 14 to provide for simultaneous filling, cooling, and removal of parts from the molds 13. Although four molds 13 are shown, it will be understood that table 14 may include any number of molds (e.g., six).

The molds 13 comprise low pressure molds having filling mechanisms that utilize low pressure casting processes having pressures of less than 500 psi, more preferably of less than 100 psi, and most preferably of less than 14.7 psi (atmospheric pressure). With further reference to Fig. 2, the illustrated, exemplary mold 13 includes a pouring basin 15, a sprue 16, and a gate 17 that are fluidly connected to a mold cavity 18. A vent 19 is also fluidly connected to the mold cavity 18. It will be appreciated that the mold 13 could include multiple mold cavities, runners, or other features as required for a particular application. The mold cavity 18 can have a relatively complex shape that produces surfaces on a casting that are finished or close to finished, such that additional machining or the like is minimized or eliminated. Also, if required for a particular application, a vacuum can be applied to the mold cavity 18 to promote flow of the slurry 12, or a mechanical force can be applied to the slurry 12 in the pouring basin 15, such as by application of a pneumatic piston. Use of the vacuum or the mechanical force increases a pressure differential between the pouring basin side and the vent side of the slurry 12 to increase the rate of viscous flow of the slurry 12.

Because the weight percent of solids in the slurry 12 is relatively low, the slurry 12 in mold 13 must be cooled at a relatively slow rate to prevent the formation of dendritic solid particles in the slurry. The allowable cooling rate depends upon the alloy used for a particular application. Also, the cooling rate will be affected by the mold material and the geometry of the part being cast. For example, if the part to be cast includes thin wall sections that tend to cool at a quicker rate, the mold cavity 18 can be designed to provide a reservoir portion that is initially filled with slurry. The slurry in the reservoir will cool at a relatively slow rate, such that the solids formed are non-
dendritic. After the percentage of solids increases to a level permitting a higher cooling rate, the slurry can be introduced into the thin wall sections of the mold.

[0029] Various suitable casting metals may be utilized in conjunction with the present application. For example, aluminum, magnesium, copper, zinc, and iron alloys can be utilized.

[0030] In the foregoing description, it will be readily appreciated by those skilled in the art that modifications may be made to the invention without departing from the concepts disclosed herein. Such modifications are to be considered as included in the following claims, unless these claims by their language expressly state otherwise.
The invention claimed is:

1. A method of forming a metal part, comprising:
   heating a metal alloy composition to form a liquid that is substantially free of metal solids;
   cooling the liquid to form a semi-solid metal alloy slurry having a weight percentage of solids in the range of about one percent to about thirty percent and being substantially free of dendritic solids;
   transferring the semi-solid metal alloy slurry to a mold;
   cooling the semi-solid metal alloy slurry in the mold at a pressure of about one hundred pounds per square inch or less to cast a substantially solid part.

2. The method of claim 1, wherein:
   the semi-solid metal alloy slurry is cast at a pressure of about fifteen pounds per square inch or less.

3. The method of claim 1, wherein:
   the semi-solid metal alloy slurry is cast at atmospheric pressure.

4. The method of claim 1, wherein:
   the substantially solid part is cast utilizing a sand casting process.

5. The method of claim 1, wherein:
   the substantially solid part is cast utilizing a lost foam casting process.

6. The method of claim 1, wherein:
   the semi-solid metal alloy slurry has a weight percentage of solids of about one percent to about twenty percent.

7. The method of claim 1, wherein:
   the semi-solid metal alloy slurry has a weight percentage of solids of about five percent to about ten percent.
8. The method of claim 1, wherein:
   the solids in the semi-solid metal alloy slurry comprise substantially spheroidal
   particles.

9. The method of claim 1, wherein:
   the metal alloy comprises aluminum.

10. The method of claim 1, wherein:
    the metal alloy comprises a titanium alloy.

11. A method of casting metallic parts, comprising:
    forming a semi-solid metal alloy slurry having a weight percentage of solids of
    about thirty percent or less, the semi-solid metal alloy slurry being substantially free of
dendritic solids;
    transferring the semi-solid metal alloy slurry to a mold having a mold cavity,
such that the semi-solid metal alloy slurry flows into the mold cavity;
    cooling the semi-solid metal alloy slurry in the mold cavity to substantially
solidify the semi-solid metal alloy slurry and form a part;
    pressurizing the semi-solid metal alloy slurry in the mold cavity at a low pressure
    as the metal alloy is cooled.

12. The method of claim 11, wherein:
    the semi-solid metal alloy slurry is cast at a pressure of about one hundred
    pounds per square inch or less.

13. The method of claim 11, wherein:
    the semi-solid metal alloy slurry comprises globular solids.

14. The method of claim 11, wherein:
    the mold further comprises a sprue and runner in fluid communication with the
    mold cavity and an upwardly opening pouring basin connected to the sprue; and
    the semi-solid metal alloy slurry is poured into the pouring basin.
15. The method of claim 11, wherein:
    the semi-solid metal alloy slurry comprises aluminum.

16. The method of claim 11, wherein:
    the mold comprises a sand mold.

17. The method of claim 11, wherein:
    the mold is fabricated by coating a wax material with a slurry.

18. The method of claim 11, wherein:
    a vacuum is applied to the mold cavity to pull the semi-solid metal alloy slurry into the mold cavity.

19. A system for making cast metallic parts, comprising:
    a furnace having a heated vessel suitable for holding liquid metal alloy;
    a semi-solid slurry production machine for producing a low fraction solid semi-solid metal alloy slurry substantially free of dendritic solids;
    a mold having a mold cavity for receiving the semi-solid metal alloy slurry at a low pressure; and
    a metal transfer device adapted to transfer the semi-solid metal alloy slurry from the semi-solid slurry production machine to the mold.

20. The system of claim 19, wherein:
    the metal transfer device is robotic.

21. The system of claim 19, wherein:
    the semi-solid slurry production machine comprises an agitating member configured to agitate the liquid metal alloy.

22. The system of claim 21, wherein:
    the agitating member is rotatable.

23. The system of claim 20, wherein:
the semi-solid metal alloy slurry comprises solids having a weight percentage of about one percent to about twenty percent.

24. The system of claim 20, wherein:

the mold cavity receives the semi-solid metal alloy slurry at about atmospheric pressure.