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(54) **METHODS FOR CASTING STAINLESS STEEL AND ARTICLES PREPARED THEREFROM**

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(57) **ABSTRACT**

A process for casting stainless steel including forming an erodable casting mold, delivering molten stainless steel into the erodable mold, contacting the erodable mold with a solvent, cooling the molten stainless steel to at least partially solidify the stainless steel and form a casting. Stainless steel castings are also provided.

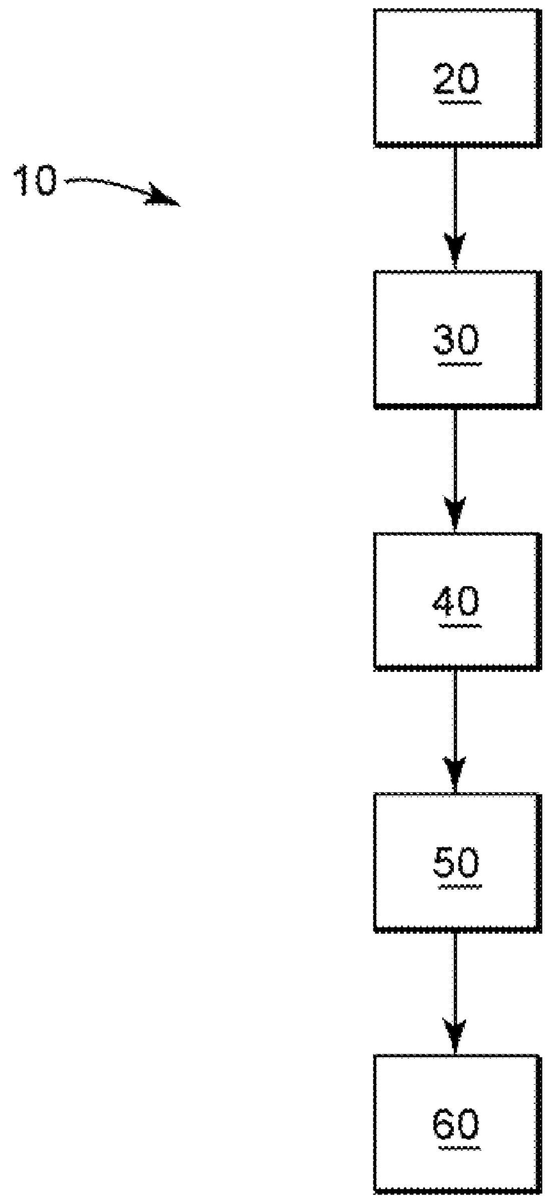
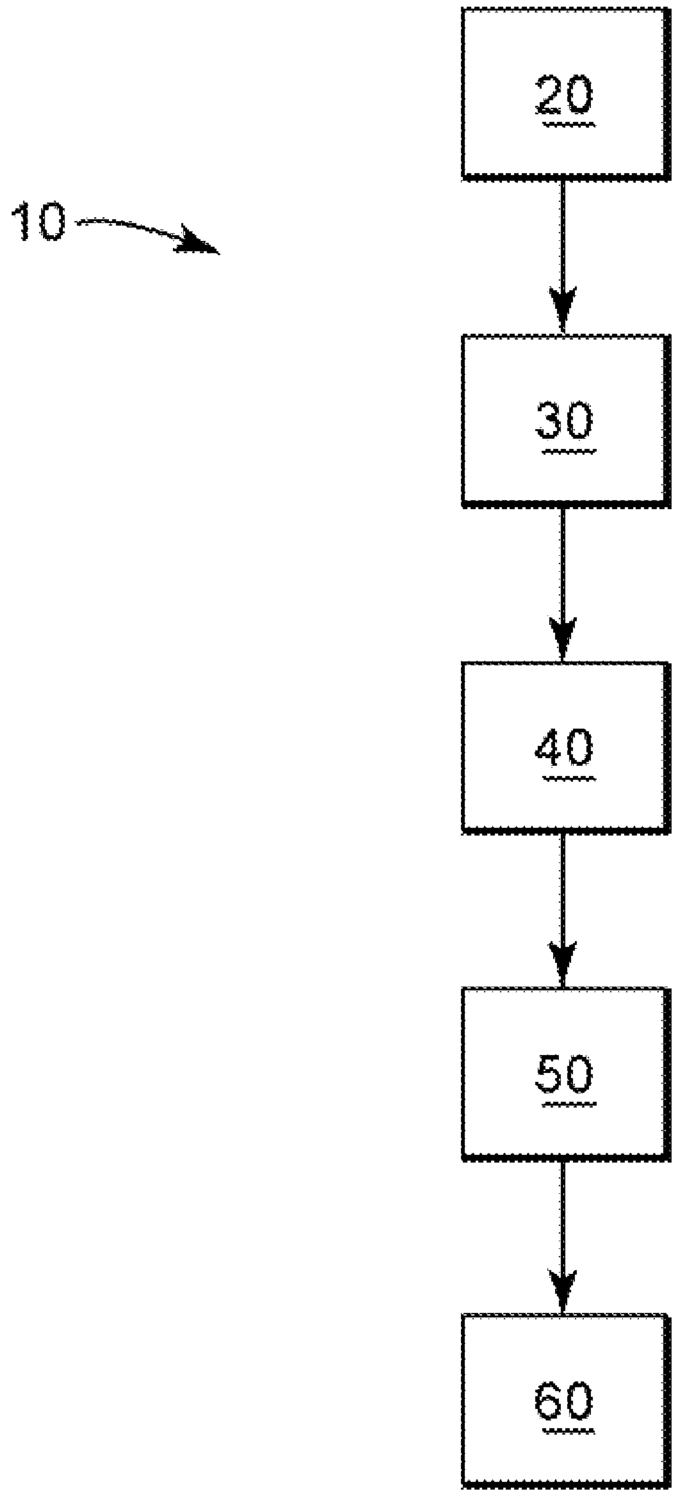


Figure 1



METHODS FOR CASTING STAINLESS STEEL AND ARTICLES PREPARED THEREFROM

FIELD OF THE INVENTION

[0001] This invention relates to castings and more particularly, to stainless steel castings.

BACKGROUND OF THE INVENTION

[0002] Stainless steel is a strong and durable material and can be used to manufacture blades, such as turbine blades. Typically, stainless steel is obtained in the form of forged bars and must be machined to manufacture the desired shape of the blade. However, using forged materials can be costly, as there is significant material loss from machining the part.

[0003] Casting blades reduces the amount of material lost from machining, because the blades are cast to a near exact shape. In a traditional casting process, molten metal is poured into a mold and solidified through a loss of heat to the mold. When enough heat has been lost from the metal and the metal solidifies, the resulting product can support its own weight and the casting can be removed from the mold. However, casting stainless steel is very difficult. Large grain sizes can form during the solidification of the molten stainless steel, which weaken the microstructure of the stainless steel. A rapid solidification of the molten metal produces a fine microstructure, which improves the mechanical properties of the casting.

[0004] Metal molds offer rapid solidification, but are expensive to machine and can introduce deformities, such as air bubbles, into the cast metal.

[0005] Sand molds are composed of a particulate or granular material, typically sand, which is held together with a binder, such as a mixture of clay and water. These molds may be manufactured rapidly and can be used in automated mold-making plants. Unfortunately, sand has a slow cooling rate, which will produce stainless steel castings with large grain sizes.

[0006] It would be desirable to improve sand castings for stainless steel by providing rapid solidification of the molten stainless steel and to provide substitutions for costly forged materials.

SUMMARY OF THE INVENTION

[0007] In one embodiment, a process for casting stainless steel, said process comprising forming an erodable casting mold, delivering molten stainless steel into the erodable mold, contacting the erodable mold with a solvent and cooling the molten stainless steel to at least partially solidify the stainless steel and form a casting.

[0008] In another embodiment, a stainless steel casting obtained by the process comprising forming an erodable casting mold, delivering molten stainless steel into the erodable mold, contacting the erodable mold with a solvent and cooling the molten stainless steel to at least partially solidify the stainless steel and form a casting.

[0009] The various embodiments reduce cooling times for stainless steel castings and provide improved stainless steel castings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. **1** is a flowchart depicting an exemplary embodiment of a method for casting stainless steel.

DETAILED DESCRIPTION OF THE INVENTION

[0011] The singular forms "a," "an" and "the" include plural referents unless the context clearly dictates otherwise. The endpoints of all ranges reciting the same characteristic are independently combinable and inclusive of the recited endpoint. All references are incorporated herein by reference.

[0012] The modifier "about" used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., includes the tolerance ranges associated with measurement of the particular quantity).

[0013] "Optional" or "optionally" means that the subsequently described event or circumstance may or may not occur, or that the subsequently identified material may or may not be present, and that the description includes instances where the event or circumstance occurs or where the material is present, and instances where the event or circumstance does not occur or the material is not present.

[0014] In one embodiment, a process for casting stainless steel, said process comprising forming an erodable casting mold, delivering molten stainless steel into the erodable mold, contacting the erodable mold with a solvent and cooling the molten stainless steel to at least partially solidify the stainless steel and form a casting.

[0015] Stainless steel is an iron-carbon alloy having at least 9 percent by weight chromium. In one embodiment, the stainless steel comprises from about 0.05 to about 1.20 percent by weight carbon, from about 9 to about 22 percent by weight chromium, up to about 1.00 percent by weight manganese, up to about 1.00 percent by weight silicon, up to about 0.045 percent by weight phosphorous, up to about 0.030 percent by weight sulfur, up to about 0.75 percent by weight nickel, up to about 0.75 percent by weight titanium with the remainder iron, based on the weight of the composition. Examples of stainless steel include, but are not limited to stainless steel grade 409, stainless steel grade 410, stainless steel grade 420 or stainless steel grade 440.

[0016] An erodable casting mold is formed for casting molten stainless steel. The erodable mold is formed by obtaining a pattern and applying an erodable aggregate material to the pattern. The pattern represents the desired shape of the stainless steel casting and may be any type of conventional pattern. In one embodiment, the pattern is for a blade. In another embodiment, the pattern is for a turbine blade. In another embodiment, the pattern is for a rotating turbine blade or for a stationary turbine blade.

[0017] In one embodiment, the pattern is reusable and is prepared from wood, metal or plastic. In another embodiment, the pattern is a lost pattern, which is not reusable. It is sacrificed during the process of preparing the casting. A lost pattern may be prepared from a variety of materials, such as foam, wax, frozen mercury or frozen water. In one embodiment, foam is used to prepare the pattern. Foam beads, such as polystyrene, are injected into a cavity in a metal die, such as an aluminum die. The foam beads are expanded by steam to fill the cavity and form a pattern that conforms to the shape of the cavity. The pattern is then removed from the die. To form a more complex pattern, several individually formed patterns may be glued together.

[0018] The lost pattern may be coated before the erodable aggregate material is applied to the pattern to support the mold. The lost pattern may be coated with any suitable coating for casting molten stainless steel, such as a ceramic coating.

[0019] The erodable aggregate material is applied to the pattern to form an erodable casting mold. The erodable material may be applied in any conventional manner. In one embodiment, the erodable material is packed around the pattern. In another embodiment, the erodable material is coated onto the pattern. The erodable material may be coated onto the pattern in any conventional manner, including, but not limited to, dipping the pattern into a slurry of the erodable material or brushing, rolling or spray coating the erodable material onto the pattern.

[0020] For the reusable patterns, the pattern is removed from the erodable aggregate material forming a cavity in the erodable mold. For complex molds, several individually formed erodable molds may be glued together to form a single erodable mold. In one embodiment, the erodable mold may be cured or dried. The mold may be cured or partially cured while in the pattern or may be cured or completely cured after removal from the pattern. In one embodiment, the erodable mold is placed in either a conventional or microwave oven. In another embodiment, the erodable mold may be placed on a perforated plate for drawing air through the mold and improve curing or drying. In one embodiment, the erodable mold is cured or dried at a temperature of 50° C. or higher.

[0021] The erodable aggregate material comprises a particulate material and a binder. The particulate material comprises granular material including, but not limited to, crushed pumice, silica sand, ceramic, glass, volcanic glass, refractory micro-bubbles, cenospheres or mixtures of the foregoing. Other types of volcanic glass, such as perlite, may also be used. In one embodiment, the particulate material is a mixture of pumice and silica sand. The pumice may be, for example, siliceous in composition (rhyolite or dacite) or basaltic (reticulate). In one embodiment, the ratio of pumice to sand is from about 2:1 to about 6:1 by volume. In another embodiment, the ratio of pumice to sand is about 3:1 by volume.

[0022] The binder bonds with the particulate material to form an aggregate. In one embodiment, the binder is water-soluble. In one embodiment, the binder comprises phosphate glass. Phosphate glass is an amorphous, water-soluble material that includes phosphoric oxide, P_2O_5, as the principal constituent with other compounds such as alumina and magnesia or sodium oxide and calcium oxide. In another embodiment, the binder includes inorganic silicates, such as sodium silicate, borates and magnesium sulfate.

[0023] The particulate material and binder are blended together, optionally, with a solvent to form an aggregate. The binder and particulate material can be mixed either by hand or with a mechanical mixer to form a uniformly moist aggregate mixture.

[0024] A solvent may be blended with the binder to aid in uniformly dispersing the binder with the particulate material. In one embodiment, the solvent is water.

[0025] The proportion of the binder and the particulate material in the erodable molding is determined by the viscosity needed to effectively apply the erodable material to the pattern. For example, the proportion should yield a workable slurry that allows the erodable material to coat all exterior surfaces of the pattern, while remaining thick enough to support the pattern and provide an effective containment of the molten metal. The erodable material may include other additives that are known in the art to aid in wetting and in the reduction of foaming. In one embodiment, the binder is present from about 5 percent by weight to about 15 percent by weight, based on the weight of the particulate material.

[0026] For erodable molds prepared from lost patterns, a backing may be used to support the erodable mold. The backing material may be any conventional type of material. In one embodiment, the backing is an unbonded particulate material, such as silica. In another embodiment, the backing is an erodable backing material.

[0027] In one embodiment, the erodable mold is placed inside a container, such as a flask, and unbonded particulate backing material is added to the container to surround and support the erodable mold.

[0028] In another embodiment, the backing is an erodable backing, which is applied to an erodable mold, such as by packing the erodable backing around the erodable mold. The erodable backing provides support to the erodable mold and provides a free-standing mold, which eliminates the need for a container to hold the erodable mold and the backing.

[0029] In another embodiment, the backing is an erodable backing, which is applied to a lost pattern, such as by packing, to form an erodable mold. The erodable backing combines the erodable coating with the erodable backing so that there is one layer of an erodable aggregate material about the pattern that acts to both contain the molten metal and provide support. In this embodiment, the erodable backing may be directly placed on the pattern, without the need for a separate coating. The erodable backing is of a sufficient viscosity to appropriately coat the surface of the pattern.

[0030] The erodable backing comprises a particulate material and a binder. The particulate material comprises granular material including, but not limited to, crushed pumice, silica sand, ceramic, glass, volcanic glass, refractory micro-bubbles, cenospheres or mixtures of the foregoing. Other types of volcanic glass such as perlite may also be used. In one embodiment, the particulate material is a mixture of pumice and silica sand. The pumice may be, for example, siliceous in composition (rhyolite or dacite) or basaltic (reticulate). In one embodiment, the ratio of pumice to sand is from about 2:1 to about 6:1 by volume. In another embodiment, the ratio of pumice to sand is about 3:1 by volume.

[0031] The binder bonds with the particulate material to form an aggregate. In one embodiment, the binder is water-soluble. In one embodiment, the binder comprises phosphate glass. Phosphate glass is an amorphous, water-soluble material that includes phosphoric oxide, P_2O_5, as the principal constituent with other compounds, such as alumina and magnesia or sodium oxide and calcium oxide. In another embodiment, the binder includes inorganic silicates, such as sodium silicate, borates and magnesium sulfate.

[0032] The particulate material and binder are blended together, optionally, with a solvent to form an aggregate. The binder and particulate material can be mixed either by hand or with a mechanical mixer to form a uniformly moist aggregate mixture.

[0033] A solvent may be blended with the binder to aid in uniformly disperse the binder with the particulate material. In one embodiment, the solvent is water.

[0034] The proportion of the mixture of the binder and the particulate material in the erodable molding is determined by the viscosity needed to effectively apply the erodable material to the pattern and to support the erodable mold. In one embodiment, the binder is present in an amount of from about 5 percent by weight to about 15 percent by weight, based on the total weight of the aggregate erodable material. In another embodiment, the particulate material is present in an amount of from about 85 percent by weight to about 95 percent by weight, based on the total weight of the aggregate erodable material.

[0035] Molten stainless steel is delivered to the erodable mold. The molten stainless steel fills the mold, using any conventional method. For example, the mold may be designed to allow the molten stainless steel to flow into the mold by gravity or it may be counter-gravity filled using low pressure or a pump. In one embodiment, a runner or conduit is attached to the pattern and the molten stainless steel is poured into the runner via a crucible or other source for molten metal. In another embodiment, the erodable mold is heated to increase the flow of the molten stainless steel and ensure that the molten stainless steel is dispersed throughout the entire mold.

[0036] In one embodiment, stainless steel is molten at temperatures of 1525° C. or above. In another embodiment, the molten stainless steel has a temperature in a range of from about 1550° C. to about 1700° C.

[0037] When the molten stainless steel is delivered into lost pattern erodable molds, the pattern is destroyed as the molten stainless steel replaces the pattern. The erodable coating or erodable backing supports the molten stainless steel until it solidifies. For example, in a lost pattern foam mold, the molten stainless steel rapidly decomposes and vaporizes the foam beads.

[0038] In one embodiment, foam patterns in the erodable mold may be removed prior to delivering the molten stainless steel. The foam beads may be eliminated by very hot gas, such as heated air or the mold may be placed in a heated furnace enclosure.

[0039] After the molten stainless steel is delivered to the erodable mold, the erodable mold is subjected to the action of a solvent. The binder in the erodable mold is soluble and dissolves in the solvent, which causes the erodable mold to decompose. As the erodable mold breaks, the molten stainless steel is directly chilled in a stream of a solvent for rapid solidification to obtain finer microstructures.

[0040] The solvents may contact the erodable molds by any conventional manner, such as by spraying the contacting solvents on the erodable mold, directing the solvent to the erodable mold via an impeller or over a waterfall or by dipping or immersing the erodable mold in the contacting solvent.

[0041] The contacting solvent may be liquids or gases that decompose the binder and cool the cast stainless steel. In one embodiment, the contacting solvent is water. Water has high heat capacity and latent heat of evaporation, allowing it to absorb a significant amount of heat before evaporating and provide an optimum cooling effect to enable rapid solidification of the cast stainless steel. The water can be at ambient temperature or can be heated. In one embodiment, steam is used as the contacting solvent.

[0042] In one embodiment, the contacting solvent contacts the erodable mold by spraying the solvent on the erodable mold. In another embodiment, the contacting solvent is sprayed by a spray nozzle that directs a jet of the solvent at the erodable mold. The jet may be delivered in any suitable configuration from a narrow stream to a wide fan and may be a steady stream or a pulsating stream.

[0043] In one embodiment, the erodable mold is supported by a backing. In another embodiment, an unbound backing material is used with the erodable mold. In one embodiment, the erodable mold may be removed from the unbound backing material and contacted with the contacting solvent. In another embodiment, the contacting solvent contacts the unbound backing material pushing it away from the erodable mold and out of the container. When at least a portion of the unbonded particulate material is removed, the contacting solvent contacts the erodable coating to decompose it. In another embodiment, the backing is erodable backing, which is first contacted by the contacting solvent. Once the backing is decomposed in a particular area, the solvent continues to be delivered to any erodable coating to cause the coating to decompose as well.

[0044] The rate and pressure of delivery of the jet are of a setting that is high enough to decompose the erodable backing and the erodable coating, yet low enough to allow the solvent to percolate through the erodable mold so that percolated solvent arrives at the cast metal ahead of the full force of the jet. In one embodiment, the contacting solvent is delivered at high volume and low pressure in a range of about 0.5 to 50 liters per second at a pressure ranging from 0.03 to 70 bar. In this manner, the percolated solvent causes the formation of a relatively solid skin on the cast stainless steel before the metal is contacted by the force of the jet, which prevents distortion of the metal or explosion from excessive direct contact of the contacting solvent with the molten stainless steel.

[0045] Surfactants may be added to the erodable mold to enhance percolation of the solvent through the erodable mold. In addition, at least some of the heat that is absorbed from the molten stainless steel by the erodable mold may increase the temperature of the contacting solvent as the solvent percolates through, which increases the energy of the solvent and causes it to erode the mold more rapidly.

[0046] In another embodiment, multiple nozzles may be used to contact the erodable molds with contact solvents. In another embodiment, combinations of solvents and/or temperatures may be employed. For example, some nozzles deliver jets of one solvent, while other nozzles deliver jets of a different solvent. In another embodiment, some nozzles deliver solvents at a first temperature, while other nozzles deliver solvents at a different temperature.

[0047] The cast stainless steel is exposed to the contacting solvent as the erodable mold decomposes and causes the cast stainless steel to cool rapidly and solidify. This rapid cooling process results in a casting with a fine microstructure and advantageous mechanical properties. After the metal has solidified and cooled, the casting is separated from the erodable mold. In another embodiment, the casting can be further cooled after the mold is removed by continuing to spray the casting with the contacting solvent.

[0048] In another embodiment, a stainless steel casting is obtained by the process comprising forming an erodable casting mold, delivering molten stainless steel into the erodable mold, contacting the erodable mold with a solvent and cooling the molten stainless steel to at least partially solidify the stainless steel and form a casting.

[0049] The stainless steel casting is rapidly cooled and forms a fine microstructure. The cast stainless steel is strong and durable and is comparable to forged stainless steel. In one embodiment, the grain sizes in the cast stainless steel have a diameter of 50 μm or less. In another embodiment, the average diameter of the grain sizes is in the range of from about 20 μm to about 50 μm.

[0050] In one embodiment, the casting is for a blade. The blade may be any type of blade used in wind, gas or steam operations. In one embodiment, the blade is a turbine blade. In another embodiment, the turbine blade is a stationary turbine blade or a rotating turbine blade.

[0051] FIG. **1** shows an exemplary embodiment of a method (**10**) for casting stainless steel. An erodable casting mold (**20**) is formed. The erodable casting mold (**20**) is prepared by obtaining a pattern and applying an erodable aggregate material to the pattern. The erodable aggregate material comprises particulate material and a binder.

[0052] The pattern is the desired shape of the article to be cast. In one embodiment, the pattern is for a blade. In another embodiment, the pattern is for a turbine blade. In another embodiment, the pattern is for a rotating turbine blade or for a stationary turbine blade.

[0053] Molten stainless steel (**30**) is delivered into the erodable casting mold (**20**). Stainless steel is heated to a temperature of 1525° C. or above. In another embodiment, the molten stainless steel has a temperature in a range of from about 1550° C. to about 1700° C.

[0054] After the molten stainless steel (**30**) is delivered to the casting mold (**20**), the erodable casting mold (**20**) is contacted by a solvent (**40**). The contacting solvent (**40**) may be liquids or gases that decompose the binder in the erodable casting mold (**20**) and cool the cast stainless steel. In one embodiment, the contacting solvent is water.

[0055] As the erodable mold (**20**) decomposes, the molten stainless steel (**30**) is directly cooled (**50**) by the application of the solvent (**40**). The molten stainless steel (**20**) rapidly solidifies to form a casting (**60**). The stainless steel casting (**60**) has a fine microstructure. In one embodiment, the grain sizes in the stainless steel casting (**60**) have a median diameter of 50 μm or less. In another embodiment, the average diameter of the grain sizes is in the range of from about 20 μm to about 50 μm.

[0056] While typical embodiments have been set forth for the purpose of illustration, the foregoing descriptions should not be deemed to be a limitation on the scope herein. Accordingly, various modifications, adaptations and alternatives may occur to one skilled in the art without departing from the spirit and scope herein.

1. A process for casting stainless steel, said process comprising forming an erodable casting mold, delivering molten stainless steel into the erodable mold, contacting the erodable mold with a solvent and cooling the molten stainless steel to at least partially solidify the stainless steel and form a casting.

2. The process of claim **1** wherein forming an erodable casting mold comprises obtaining a pattern and applying an erodable aggregate material to the pattern.

3. The process of claim **2** wherein the pattern is for a blade.

4. The process of claim **3**, wherein the blade is a turbine blade.

5. The process of claim **2**, wherein the pattern is reusable.

6. The process of claim **2**, wherein the pattern is a lost pattern.

7. The process of claim **6** wherein the lost pattern comprises a material selected from the group consisting of foam, wax, frozen mercury and frozen water.

8. The process of claim **7** wherein the lost pattern comprises foam.

9. The process of claim **6** wherein the lost pattern is coated.

10. The process of claim **9** wherein the coating is a ceramic coating.

11. The process of claim **2** wherein the erodable aggregate material is applied to the pattern by packing the erodable material around the pattern or by coating the erodable material onto the pattern.

12. The process of claim **2** wherein the erodable aggregate material comprises a particulate material and a binder.

13. The process of claim **12** wherein the particulate material is selected from the group consisting of crushed pumice, silica sand, ceramic, glass, volcanic glass, refractory micro-bubbles, cenospheres and mixtures of the foregoing.

14. The process of claim **13** wherein the binder comprises materials selected from the group consisting of phosphate glass, inorganic silicates, borates and magnesium sulfate.

15. The process of claim **12**, wherein the binder is present from about 5 percent by weight to about 15 percent by weight and the particulate material is present from about 85 to about 95 percent by weight, based on the total weight of the aggregate erodable material.

16. The process of claim **6** wherein the mold comprises a backing to support the erodable mold.

17. The process of claim **16** wherein the backing material is an erodable backing material.

18. The process of claim **17**, wherein the erodable backing is applied to an erodable mold, such as by packing the erodable backing around the erodable mold.

19. The process of claim **17** wherein erodable backing comprises a particulate material and a binder.

20. The process of claim **19** wherein the particulate material comprises a material selected from the group consisting of crushed pumice, silica sand, ceramic, glass, volcanic glass, refractory micro-bubbles, cenospheres and mixtures of the foregoing.

21. The process of claim **19** wherein the binder comprises a material selected from the group consisting of phosphate glass, inorganic silicates, borates and magnesium sulfate.

22. The process of claim **1** wherein the solvent contacts the erodable mold by spraying the solvent on the erodable mold or by immersing the erodable mold in the contacting solvent.

23. The process of claim **1** wherein the contacting solvent comprises water.

24. The process of claim **22** wherein multiple nozzles are used to spray the solvent on the erodable mold.

25. A stainless steel casting obtained by the process comprising forming an erodable casting mold, delivering molten stainless steel into the erodable mold, contacting the erodable mold with a solvent, cooling the molten stainless steel to at least partially solidify the stainless steel and form a casting.

26. The stainless steel casting of claim **25** wherein the stainless steel has a fine microstructure comprising grain sizes having an average diameter of 50 μm or less.

27. The stainless steel casting of claim **26** wherein the average diameter for the grain sizes is in the range of from about 20 μm to about 50 μm.

28. The stainless steel casting of claim **25** wherein the casting is a blade.

29. The stainless steel casting of claim **28** wherein the blade is a turbine blade.

30. The stainless steel casting of claim **25** wherein the turbine blade is a stationary turbine blade or a rotating turbine blade.

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