A die cast article such is composed of nickel base superalloy IN 718 is disclosed. The microstructure is characterized by an absence of flowlines and includes a fine average grain size, e.g., ASTM 3 or smaller. Exemplary articles include gas turbine engine components, such as blades, vanes, cases and seals.
FIG. 10

1. Prepare charge of material

2. Melt single charge of material in vacuum, limited superheat

3. Pour molten material to partly fill shot sleeve

4. Inject molten material into reusable die

5. Eject part

6. Post-casting processing, e.g., HIP, CHEM-MILL, media finish, etc.

7. Inspection

8. Repeat/use
DIE CAST NICKEL BASE SUPERALLOY ARTICLES

[0001] This application claims the benefit of U.S. Provisional application No. 60/113,755, filed on Dec. 23, 1998.

CROSS REFERENCE TO RELATED APPLICATIONS

[0002] Some of the material in the present application is also disclosed in co-pending applications filed on even date herewith and entitled “Method of Making Die Cast Articles of High Melting Temperature or Reactive Materials”, and “Apparatus for Die Casting High Melting Temperature Materials”, which are hereby expressly incorporated by reference herein.

BACKGROUND OF THE INVENTION

[0003] The present invention relates generally to articles fabricated from superalloy material, and relates more particularly to articles fabricated from nickel base superalloys. Such alloys typically have high melting temperatures, in excess of 2300-2500°F.

[0004] Nickel base superalloys are employed in applications which require high strength-weight ratios, corrosion resistance and use up to relatively high temperatures, e.g., up to and above about 2000°F.

[0005] In gas turbine engines for example, these superalloys are typically employed in the turbine section, and sometimes in the latter stages of the compressor section of the engine, including but not limited to airfoils such as blades and vanes, as well as static and structural components such as intermediate and compressor cases, compressor disks, turbine cases and turbine disks. A typical nickel base superalloy utilized in gas turbine engines is Inconel 718 (IN 718), in broad terms having general a composition in weight percent, of about 0.01-0.05 Carbon (C), 13-25 Chromium (Cr), 2.5-3.5 Molybdenum (Mo), 5.0-5.75 (Columbium (Cb) also referred to as Niobium (Nb)), 0.7-1.2 Tantalum (Ta), 0.3-0.9 Aluminum (Al), up to about 21 Iron (Fe), balance generally Ni.

[0006] In the gas turbine engine industry, forging is used to produce parts having complex, three-dimensional shapes such as blades and vanes. Nickel base superalloys have traditionally been precision forged to produce parts having a fine average grain size and a balance of high strength, low weight, and good high cycle fatigue resistance. When properly produced, these parts do exhibit a balance of high strength, low weight, and durability.

[0007] Briefly, in order to forge a part such as a blade of vane, an ingot of material is first obtained having a composition corresponding to the desired composition of the finished component. The ingot is converted into billet form, typically cylindrical for blades and vanes, and is then thermomechanically processed, such as by heating and stamping several times between dies and/or hammers which may be heated and are shaped progressively similar to the desired shape, in order to plastically deform and flow the material into the desired component shape. Each component is typically treated to obtain desired properties, e.g., hardening/strengthening, stress relief, resistance to crack nucleation and a particular level of HCF resistance, and is also finished, e.g., machined, chem-milled and/or media finished, as needed to provide the component with the precise shape, dimensions or features.

[0008] The production of components by forging is an expensive, time consuming process, and thus is typically warranted only for components that require a particular balance of properties, e.g., high strength, low weight and durability, both at room temperature and at elevated temperatures. With respect to obtaining material for forging, certain materials require long lead times, sometimes measured in months. Forging typically includes a series of operation, each requiring separate dies and associated equipment. The post-forging finishing operations, e.g., machining the root portion of a blade and providing the appropriate surface finish, comprise a significant portion of the overall cost of producing forged parts, and include a significant portion of parts which must be scrapped.

[0009] During component forging, much of the original material (up to about 85%) is removed and does not form part of the finished component, e.g., it is process waste. The complexity of the shape of the component produced merely adds to the effort and expense required to fabricate the component, which is an even greater consideration for gas turbine engine components having particularly complex shapes. Nickel base superalloys such as IN 718 also exhibit significant springback, e.g., the material is resilient, and the springback must be taken into account during forging, i.e., the parts must typically be “over forged”. As noted above, finished components may still require extensive post forging processing. Moreover, as computer software is used to apply computational fluid dynamics to analyze and generate more aerodynamically efficient airfoil shapes, such airfoils and components have even more complex three-dimensional shapes. It is correspondingly more difficult or impossible to forge superalloys precisely into these advanced, more complex shapes, e.g., due in part to the slightly resilient nature many materials exhibit during forging, which adds further to the cost of the components or renders the components so expensive that it is not economically feasible to exploit certain advances in engine technology, or to utilize particular alloys for some components.

[0010] Forged components also often exhibit significant levels of defects, including inclusions and carbides, which vary significantly from component to component. Such components having higher columbium contents, e.g., IN 718, are also prone to elemental segregation during forging. In addition, forged components tend to be difficult to machine and inspect for such defects. Moreover, precise reproducibility is also a concern—forging does not result in components having dimensions that are precisely the same from part to part. After inspection, many parts must still be re-worked. As a general rule, forged parts must be scrapped or significantly re-worked about 20% of the time. Moreover, newer, more advanced or more highly alloyed nickel base superalloys (e.g., Waspaloy or IN 939) will be increasingly difficult (if not impossible) and correspondingly more expensive to forge. These concerns will only intensify as more complex three-dimensional airfoil geometries are employed.

[0011] Casting has been extensively used to produce relatively near-finished-shape articles.

[0012] Investment casting, in which molten metal is poured into a ceramic shell having a cavity in the shape of
the article to be cast, can be used to produce such articles. However, investment casting produces articles having extremely large grains (relative to the small average grain size achievable by forging), and in some cases the entire part comprises a single grain. In addition, solidification rates may result in the presence of unacceptable amounts of elemental segregation producing large scatter (variances from part to part) in test results or in the presence of brittle phases also resulting in reduced properties. Moreover, since an individual mold is produced for each part, this process is expensive. Reproducibility of very precise dimensions from part to part is difficult to achieve. In addition, molten material is melted, poured and/or solidified in air or other gas, results in parts having undesirable properties such as inclusions and porosity, particularly for materials containing reactive elements.

[0013] Permanent mold casting, in which molten material is poured into a multipart, reusable mold and flows into the mold under only the force of gravity, has also been used to cast parts generally. See, e.g., U.S. Pat. No. 5,505,246 to Colvin. However, permanent mold casting has several drawbacks. For thin castings, such as airfoils, the force of gravity may be insufficient to urge the material into thinner sections, particularly so where high melting temperature materials and low superheats are employed, and accordingly the mold does not consistently fill and the parts must be scrapped. Dimensional tolerances must be relatively large, and require correspondingly more post casting work, and repeatably is difficult to achieve. Permanent mold casting also results in relatively poor surface finish, which also requires more post cast work.

[0014] Die casting, in which molten metal in injected under pressure into a reusable die, has been used successfully in the past to form such articles from materials having relatively low-melting temperatures, e.g., Ti66 below about 2000 F.

[0015] One type of die casting machine is set forth in U.S. Pat. No. 3,791,440. In that patent, the machine includes a fixed die element 11 and a moveable die element 12. Briefly, metal which has been melted is poured through a pour spout 22 and sprue 21, and flows into an injection cylinder 30, which communicates with the die cavity 15. Sufficient molten material is poured to fill the injection cylinder 30 and a portion of the sprue 21, thus displacing air from the injection cylinder. See, e.g., col. 6, lines 7-17. An injection plunger 38 forces material from the injection cylinder 30 into the die cavity 15. A sprue locking cylinder and associated plunger 35 can seal the sprue 21, e.g., during injection. The injection cylinder 30 is embedded in one of the die platens, thereby preventing distortion of the cylinder when high melting temperature, molten material is poured into the injection cylinder. The Cross-type machine does not utilize a vacuum environment, but rather utilizes complete filling of the cylinder to prevent injecting air into the die.

[0016] Such machines are expensive. Moreover, this type of machine is not readily available, and is correspondingly expensive to refurbish and repair, as needed. For example, it would be difficult and expensive at best to attach a vacuum system to the machine, since the sleeve is embedded in a platen and not readily accessible. Moreover, it would be difficult at best to transfer molten material from a melting unit to the pour spout 22, within a vacuum environment controlling the temperature of the die would also be difficult, not only due to the physical size of the platen/embodied die combination, but also due to the thermal mass of such a combination. The configuration of the machine would also render release of the part difficult within a vacuum environment.

[0017] Another type of die casting machine is the “cold chamber” type. As set forth, for example, in U.S. Pat. Nos. 2,932,865, 3,106,002, 3,532,561 and 3,646,990, a conventional, cold chamber die casting machine includes a shot sleeve mounted to one (typically) fixed platen of a multiple part die, e.g., a two part die including fixed and movable platens which cooperate to define a die cavity. The shot sleeve can be oriented horizontally, vertically or inclined between horizontal and vertical. The sleeve communicates with a runner of the die, and includes an opening on top of the sleeve through which molten metal is poured. A plunger is positioned for movement in the sleeve, and forces molten metal that is present in the sleeve into the die. In a “cold type” machine, the shot sleeve is oriented horizontally and is unheated. Casting typically occurs under atmospheric conditions, i.e., the equipment is not located in a non-reactive environment such as a vacuum chamber.

[0018] The drawbacks of such machines are discussed in U.S. Pat. No. 3,646,990, particularly in connection with the inability to use such machines to cast higher melting point materials (Tm above about 2000 F), such as nickel base, cobalt base and iron base superalloys. In conventional cold chamber machines the shot sleeve is not evacuated, and the plunger also forces air into the die resulting in undesirable and impermissible porosity of die cast articles. Accordingly, in order to avoid injecting bubbles with the molten material the shot sleeve must be filled as completely as possible, or is inclined such that any air in the molten material migrates away from the die before injection.

[0019] Moreover, since the shot sleeve is unheated, a skin or “can” of molten metal solidifies on the inside of the shot sleeve, and in order to move the plunger through the sleeve to inject the molten metal into the die, the plunger must scrape the skin off the sleeve and “crush the can”. However, where the can forms a structurally strong member, e.g., in the form of cylinder which is supported by the sleeve, the plunger and/or associated structure for moving the plunger can be damaged or destroyed. Where the sleeve is thermally distorted and fails to match the plunger shape, or the plunger is distorted and fails to match the sleeve shape, the plunger can allow the passage, of metal between plunger and sleeve (“blowback”) and/or any entrapped gas between the plunger and sleeve, all of which detrimentally affects the quality of the resulting articles. See also U.S. Pat. No. 3,533,464 to Parlanti et al.

[0020] Despite extensive efforts, the conventional “cold chamber” die casting apparatus have not been used successfully to produce articles composed of high melting temperature materials, such as nickel base superalloys. Past attempts to die cast high melting temperature materials such as superalloys has resulted in broken die casting machinery, as well as articles characterized by inferior qualities such as impurities, excessive porosity and segregation, and relatively poor strength and low and high cycle fatigue properties.
It is an object of the present invention to provide die cast articles composed of high melting temperature materials, such as nickel base superalloys.

It is another object of the present invention to provide die cast nickel base superalloy articles having properties comparable to corresponding forged articles.

It is a more specific object of the present invention to provide nickel base superalloy articles that have strength, durability and fatigue resistance comparable to corresponding forged superalloy articles.

It is still another object of the present invention to provide such articles having complex, three dimensional shapes that are difficult if not impossible to forge.

Additional objects will become apparent to those skilled in the art based upon the following disclosure and drawings.

SUMMARY OF THE INVENTION

According to one aspect of the invention, a die cast article composed of nickel base superalloy such as IN 718 is disclosed. The articles preferably at least meet the strength, low crack growth rates and stress rupture resistance requirements of corresponding forged articles, e.g., according to AMS 5663 or AMS 5383. The article, for example includes a blade or vane for a gas turbine engine. Each article has a microstructure similar to that of forged material, and is characterized by a more uniform grain, and a fine average grain size for a cast article, e.g., smaller than about ASTM 3, more preferably ASTM 5 or smaller. The microstructure preferably is further characterized by an absence of flow lines. In the case of rotating components, such as a gas turbine engine blades, the preferred average grain size is smaller, e.g., preferably ASTM 5 or smaller, more preferably ASTM 6 or smaller.

The articles have both yield and ultimate tensile strengths at both room and elevated temperatures that are comparable to forged parts composed of the same material, and also have similar high and low cycle fatigue properties.

An advantage of the present invention is that die casting significantly reduces the time required to produce a part, from ingot to finished part, as there is no need to prepare specially tailored billets of material or ceramic investment shell, and casting broadly is performed in a single step, as opposed to multiple forging operations or shell preparations. In addition, die casting enables the production of multiple parts in a single casting. Die casting further enables production of parts having more complex three dimensional shapes, thereby enabling production of more aerodynamically efficient airfoils, and other components relative to forging. The present invention will enable the production of articles utilizing materials having shapes that are difficult or impossible to forge into those shapes. Moreover, die cast parts have greater reproducibility than forged or investment cast articles, and can be produced nearer to their finished shape, and with a superior surface finish, which minimizes post forming finishing operations, all of which also reduces the cost of producing such parts. Additional advantages will become apparent in view of the following drawings and detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a view illustrating a die cast article composed of IN 718 in accordance with the present invention.

FIG. 2 is a photomicrograph illustrating the microstructure of a test bar composed of die cast IN 718 in accordance with the present invention.

FIG. 3 is a photomicrograph illustrating the microstructure of an airfoil composed of die cast IN 718 in accordance with the present invention.

FIG. 4 is a photomicrograph of the airfoil of FIG. 4 after hot isostatic pressing of the airfoil.

FIG. 5 is a photomicrograph illustrating the microstructure of an airfoil composed of forged IN 718.

FIGS. 6 and 7 illustrate properties of a die cast IN 718 article in accordance with the present invention and corresponding forged articles.

FIGS. 8 and 9 are schematic views of a die casting machine used to produce articles composed of IN718.

FIG. 10 is a flow diagram illustrating a process of die casting IN 718 in accordance with the present invention.

FIG. 11 is an exemplary heat treatment to reduce or eliminate elemental segregation on a microscopic level.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Turning now to FIG. 1, a die cast nickel base superalloy article in accordance with the present invention is indicated generally by the reference numeral 10. In the illustrated embodiment, the article includes a blade 10 composed of IN 718 and which is used in a gas turbine engine. The article includes an airfoil 12, a platform 14, and a root 16. The present invention is broadly applicable to various applications, and is not intended to be limited to any particular article or to use in gas turbine engines. Preferably, the die cast components for use in a gas turbine engine (as opposed to die cast components for other applications) exhibit strengths, low crack growth rates and high stress rupture resistance set forth in Aerospace Material Specification AMS 5663 (Rev. J, publ. Sep. 1997) (for corresponding forged components) or AMS 5383 (Rev. D, publ. Apr. 1993) (for corresponding investment cast components for lower strength applications relative to AMS 5663) published by SAE Int’l of Warrendale, PA, and incorporated by reference herein.

As noted above, a typical nickel base superalloy utilized in gas turbine engines is Inconel 718 (IN 718), which generally includes in weight percent about 19 Cr, 3.1 Mo, about 5.3 (Cb+Ta), 0.9 Ti, 0.6 Al, 19 Fe, balance.

More broadly, IN 718 includes in weight percent, about 0.01-0.05 Carbon (C), up to about 0.4 Manganese (Mn), up to about 0.2 Silicon (Si), 13-25 Chromium (Cr), up to about 1.5 Cobalt (Co), 2.5-3.5 Molybdenum (Mo), 5.0-5.75 (Columbium (Cb)+Tantalum (Ta), 0.7-1.2 Titanium (Ti), 0.3-0.9 Aluminum (Al), up to about 21 Iron (Fe), balance essentially Ni. Still more preferably, IN718 has a composition of about 0.02-0.04 C, up to about 0.35 Mn, up to about 0.15 Si, 17-21 Cr, up to about 1 Co, 2.8-3.3Mo+W+Re, 5.15-5.5 Cb+Ta, 0.75-1.15 Ti+V+Hf, 0.4-0.7 Al, up to about 19 Fe, balance.
essentially Ni. Other elements (also by weight percent) may also include up to about 0.01 Sulfur (S), up to about 0.015 Phosphorus (P), 0.002-0.006 Boron (B), up to about 0.10 Cu, up to about 0.0030 Magnesium (Mg), up to about 0.006 Lead (Pb), up to about 0.0060 Bismuth (Bi), up to about 0.0003 Selenium (Se), up to about 0.0005 Silver (Ag), up to about 0.01 Oxygen (O) and, up to about 0.01 Nitrogen (N).

[0040] Compositional modifications can be made to IN 718, e.g., increasing the Nb content of the material to be cast, as well as other strengthening elements to improve strength and capability.

[0041] We have produced die cast articles composed of nickel base superalloys using a die casting machine of the type shown and described, e.g., in U.S. Pat. Nos. 3,791,440 and 3,810,505 both to Cross. We have also die cast such articles in “cold chamber type” die casting machines, typically having an unheated shot sleeve and as described above and in the ‘440 patent. We have subsequently used and prefer to use the “cold chamber” machines in connection with the present invention, at least since such machines are less expensive, more readily available, may be refurbished as needed for use in die casting such high melting temperature materials, and are generally less expensive to repair if needed.

[0042] Briefly, in accordance with the present invention at least a single charge of material is melted in a manner to minimize contamination, either in connection with the melting apparatus or from reaction of one or more elements of the material. Accordingly, the alloy is heated and melted in a non-reactive, e.g., an inert or preferably in a vacuum environment, preferably maintained at a pressure of less than 100 μm more preferably at less than 50 μm. The alloy is also heated to a controlled, limited superheat, e.g., typically within 100°F to 200°F above the melting temperature of the alloy and more preferably within 50°F to 100°F, and preferably using a non-contaminating melting device. We prefer to use a ceramic free melting system such as an inducto-skull melting unit. The material is sufficiently superheated to ensure that it remains molten until injected into the die, but not enough to prevent rapid solidification of the molten material after injection. Molten alloy is then transferred to a horizontal shot sleeve of the machine, which is preferably located in a vacuum environment and the molten material is injected under pressure into a reusable mold. The process comprising pouring and injecting the molten material should not exceed a few seconds, with injection occurring preferably in less than one or two seconds, in a die casting machine having an unheated shot sleeve.

[0043] It should be noted that the articles may be thermomechanically processed after casting, if desired. In other words, the articles may be forged after being die cast; e.g., the die cast articles may serve as pre-forms for use in a forging operation. We prefer that the die cast articles be cast to near net shape, so as to minimize post-casting work and associated expertise performed on the articles.

[0044] In accordance with the present invention, articles prepared in accordance with the present invention are characterized by a microstructure having a fine, uniform average grain size, particularly for cast articles, and an absence of flow lines. See, FIGS. 2 and 3 illustrating the microstructure of a die cast IN 718 test bar and an airfoil, respectively, and FIG. 5 illustrating the microstructure of a conventional, forged IN 718 airfoil. In FIG. 2, the average grain size is roughly ASTM 6. In FIG. 5, the average grain size is roughly ASTM 10.

[0045] The articles are characterized by a small average grain size, e.g., for non-rotating gas turbine engine components such as cases and seals, the average grain size is ASTM 3 or smaller, more preferably ASTM 5 or smaller. In the case of rotating components, such as gas turbine engine blades, the preferred average grain size is smaller, e.g., preferably ASTM 5 of smaller, more preferably ASTM 6 or smaller. The preferred average grain size and maximum allowable grain size will depend upon the application of the part, e.g., whether the article is intended for use in a gas turbine engine versus other application, rotating vs. non-rotating parts, operating in lower temperature versus higher temperature environments. Such articles have properties comparable to, and preferably at least equivalent to, corresponding articles composed of forged material.

[0046] Surprisingly however, the die cast Inconel 718 article still exhibited the presence of casting segregation in the as cast condition, despite the relatively fine as, cast grain size and high solidification rates. For critical applications (such as rotating turbine engine hardware), the presence of casting segregation is unacceptable. We have discovered that it is possible to thermally homogenize the casting segregation while maintaining the benefits associated with the fine as cast grain size. This can be accomplished through a short alone heat treat cycle or a careful selection of the HIP cycle temperature. See, co-pending application entitled “Heat Treatment For Die Cast Superalloy Articles”, filed on even date herewith and expressly incorporated by reference herein.

[0047] As noted above, the present invention enables the die casting of articles that have not only good strength, but also have other properties that are comparable to or better than corresponding forged components, e.g., low crack growth rates and high stress rupture resistance. Samples of die cast IN 718 in accordance with the present invention were tested to determine yield and ultimate tensile strengths, as well as ductility and impact strength. With respect to tensile properties, samples of die cast IN 718 articles were tested both at room temperature (about 70°F) and elevated temperatures, e.g., about 1200°F held for a period of time prior to testing. The samples were subjected to strain rate of between 0.003-0.007 in./in./minute through the yield strength, and then the rate was increased to produce failure in about one minute later. As indicated by FIGS. 6 and 7, the die cast articles are characterized, at room temperature and at elevated temperatures, by comparable 0.2% yield strengths, ultimate tensile strengths, elongation at failure and impact strengths.

[0048] More specifically, in the case of blades and vanes, e.g., rotating components, die cast parts require at least strength and impact properties equivalent to those exhibited by corresponding forged articles. Blades, vanes and rotating components composed of IN 718 should have a 0.2% yield strength at room temperature of at least 140 ksi and more preferably at least 150 ksi and most preferably at least 160 ksi; and at yield strength at 1200° F. of at least 115 ksi and more preferably 125 ksi and most preferably at least 135 ksi. Such articles have a ultimate tensile strength at room temperature of at least 175 ksi and more preferably at least 185
ksi and most preferably at least 195 ksi; and an ultimate tensile strength at 1200°F. of at least 140 ksi and more preferably 150 ksi and most preferably at least 160 ksi.

[0049] In addition, standard combination smooth and notched stress rupture test specimens (comprising material produced in accordance with the present invention), e.g., conforming to ASTM E292, were tested. The specimens were maintained at about 1200°F. and loaded continuously, after generating an initial axial stress of between about 105-110 ksi. In the case of material to be used for blades and vanes, the specimens ruptured only after at least 23 hours. The values are comparable to those found in AMS 5663, referenced above.

[0050] Similar standard combination smooth and notched stress rupture test specimens (comprising material produced in accordance with the present invention), e.g., conforming to ASTM E292, were also tested at about 1300°F. The specimens were loaded continuously, after generating an initial axial stress of between about 60-65 ksi. In the case of material to be used for blades and vanes, the specimens ruptured only after at least 40 hours.

[0051] Creep properties were also evaluated, at about 1200°F. The specimens were maintained at about 1200°F., and loaded to produce an axial stress of at least about 80 ksi. The time to 0.1% plastic deformation was measured, in the case of material to be used for blades and vanes, should exceed about 15 hours. Again, the specific required values will differ depending upon the particular use to which the articles are being put.

[0052] For non-rotating parts, such as cases, flanges and seals, e.g., rings the above values are in excess of the values required. More specifically, for non-rotating parts such as rings and seals composed of IN 718 should have a 0.2% yield strength at room temperature of at least 130 ksi and more preferably at least 140 ksi and most preferably at least 150 ksi; and at yield strength at 1200°F. of at least 105 ksi and more preferably 115 ksi and most preferably at least 125 ksi. Such articles have a ultimate tensile strength at room temperature of at least 165 ksi and more preferably at least 175 ksi and most preferably at least 185 ksi; and an ultimate tensile strength at 1200°F. of at least 125 ksi and more preferably 135 ksi and most preferably at least 145 ksi.

[0053] In addition, standard combination smooth and notched stress rupture test specimens (comprising material produced in accordance with the present invention), e.g., conforming to ASTM E292, were tested. The specimens were maintained at about 1200°F. and loaded continuously, after generating an initial axial stress of between about 105-110 ksi. In the case of material to be used for blades and vanes, the specimens ruptured only after at least 23 hours, and the elongation was at least about 6%.

[0054] Similar standard combination smooth and notched stress rupture test specimens (comprising material produced in accordance with the present invention), e.g., conforming to ASTM E292, were also tested at about 1300°F. The specimens were loaded continuously, after generating an initial axial stress of between about 60-65 ksi. In the case of material to be used for blades and vanes, the specimens ruptured only after at least 85 hours.

[0055] Creep properties were also evaluated, at about 1200°F. The specimens were maintained at about 1200°F., and loaded to produce an axial stress of at least about 80 ksi. The time to 0.1% plastic deformation was measured, in the case of material to be used for blades and vanes, should exceed about 15 hours. Again, the specific required values will differ depending upon the particular use to which the articles are being put.

[0056] AMS 5663 calls for the following properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Room Temp.</th>
<th>1200°F. +/- 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, min.</td>
<td>180 ksi</td>
<td>140 ksi</td>
</tr>
<tr>
<td>Yield Strength, 0.2% offset, min.</td>
<td>150 ksi</td>
<td>125 ksi</td>
</tr>
<tr>
<td>Elongation in 4D, min.</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Reduction in area, min.</td>
<td>12%</td>
<td>12%</td>
</tr>
</tbody>
</table>

[0057] As noted in AMS 5663, the properties for forged material differ depending upon whether the samples are tested longitudinally or transversely, e.g., the properties are not isotropic and the lower values are produced during transverse testing.

[0058] In addition, standard combination smooth and notched stress rupture test specimens (comprising material produced in accordance with the present invention), e.g., conforming to ASTM E292, are tested. The specimens were maintained at 1200°F. and loaded continuously, after generating an initial axial stress of between about 105-110 ksi. The specimens ruptured after at least 23 hours. These values meet the requirements set forth in AMS 5663.

[0059] For lower strength articles, i.e., meeting the requirements of AMS 5383 standard combination smooth and notched stress rupture test specimens are tested. The specimens were maintained at 1300°F. and loaded continuously, after generating an initial axial stress of about 65 ksi. The specimens should rupture only after at least 23 hours.

[0060] Turning to FIGS. 8, 9 and 10, such nickel base superalloys such as IN 718 are preferably melted and cast in a non-reactive environment, e.g., in the presence of an inert gas or more preferably in a vacuum environment. The preferred manner of die casting the articles is set forth in co-pending application entitled “Method of Making die Cast Articles of High Melting Temperature or Reactive Material”, and “Apparatus for Die Casting High Melting Temperature Materials”, filed on even date herewith and which are each hereby incorporated explicitly herein by reference. Preferably, a single charge or small batch (less than about 10 pounds) of material is prepared (FIG. 10, step 44). The charge is melted to ensure rapid melting without contaminating the material. The molten material is then poured into a horizontal shot sleeve of a cold chamber-type die casting apparatus, which is also preferably evacuated, so as to partially fill the sleeve. The molten material is then injected into a die, which is preferably unheated, where so is solidifies to form the desired article.

[0061] Initially, material to be die cast must first be melted (step 46-FIG. 10) in the apparatus 18 illustrated in FIGS. 8
and 9. Where reactive materials, such as superalloys containing reactive elements, are to be cast, it is important to melt the materials in a non-reactive environment, to prevent any reaction, contamination or other condition which might detrimentally affect the quality of the resulting articles. Since any gases in the melting environment may become entrapped in the molten material and result in excess porosity in die cast articles, we prefer to melt the material in a vacuum environment rather than in an inert environment, e.g., argon. More preferably the material is melted in a melt chamber 20 coupled to a vacuum source 22 in which the chamber is maintained at a pressure of less than 100 \( \mu \text{m} \), and preferably less than 50 \( \mu \text{m} \).

[0062] We prefer to melt nickel base superalloys such as IN 718 by induction skull melting or melting (ISR) 24, for example a crucible manufactured by Consarc Corporation of Rancocas, N.J. which is capable of rapidly, cleanly melting a single charge of material to be cast, e.g., up to about 25 pounds of material. In ISR, material is melted in a crucible defined by a plurality of metal (typically copper) fingers retained in position next to one another. The crucible is surrounded by an induction coil coupled to a power source 26. The fingers include passages for the circulation of cooling water from and to a water source (not shown), to prevent melting of the fingers. The field generated by the coil passes through the crucible, and heats and melts material located in the crucible. The field also serves to agitate or stir the molten metal. A thin layer of the material freezes on the crucible wall and forms the skin, thereby minimizing the ability of molten material to attack the crucible. By properly selecting the crucible and coil, and the power level and frequency applied to the coil, it is possible to urge the molten material away from the crucible, in effect levitating the molten material.

[0063] Since some amount of time will necessarily elapse between material melting and injection of the molten material into the die, the material is melted with a limited superheat-high enough to ensure that the material remains at least substantially molten until it is injected, but low enough to ensure that rapid solidification occurs upon injection, e.g., so that small grains can be formed. For superalloys, we prefer to limit the superheat to within about 200 \( ^\circ \text{F} \) over the melting point, more preferably less than 100 \( ^\circ \text{F} \), and most preferably less than 50 \( ^\circ \text{F} \).

[0064] While we prefer to melt single charges of the material using an ISR unit, the material may be melted in other manners, such as by vacuum induction melting (VIM), electron beam melting, resistance melting or plasma arc. Moreover, we do not rule out melting bulk material, e.g., several charges of material at once, in a vacuum environment and then transferring single charges of molten material into the shot sleeve for injection into the die. However, since the material is melted in a vacuum, any equipment used to transfer the molten material must typically be capable of withstanding high temperatures and be positioned in the vacuum chamber, and consequently the chamber must be relatively large. The additional equipment adds cost, and the correspondingly large vacuum chamber takes longer to evacuate thus adversely affecting the cycle time.

[0065] In order to transfer molten material from the crucible to a shot sleeve 30 of the apparatus (step 48 - FIG. 10), the crucible is mounted for translation (arrow 32 in FIG. 9), and also for pivotal movement (arrow 33 of FIG. 8) about a pouring axis (not shown), and in turn is mounted to a motor (also not shown) for rotating the crucible to pour molten material from the crucible through a pour hole 32 of the shot sleeve 30, with or without a pour cup or funnel coupled to the sleeve. Translation occurs between the melt chamber 20 in which material is melted and a position in a separate vacuum chamber 34 in which the shot sleeve is located. The pour chamber 34 is also maintained as a non-reactive environment, preferably a vacuum environment at a pressure less than 100 \( \mu \text{m} \), and more preferably less than 50 \( \mu \text{m} \). The melt chamber 20 and pour chamber 34 are separated by a gate valve or other suitable means (not shown) to minimize the loss of vacuum in the event that one chamber is exposed to atmosphere, e.g., to gain access to a component in the particular chamber.

[0066] As noted above, the molten material is transferred from the crucible 24 into the shot sleeve 30 through a pour hole 34. The shot sleeve 30 is coupled to a multipart, reusable die 36, which defines a die cavity 38. A sufficient amount of molten material is poured into the shot sleeve to fill the die cavity, which may include one part or more than one part. We have successfully cast as many as 12 parts in a single shot, e.g., using a 12 cavity die.

[0067] The illustrated die 36 includes two parts, 36a, 36b, which cooperate to define the die cavity 38, for example in the form of a compressor airfoil for a gas turbine engine. The die 36 is also coupled to the vacuum source, to enable evacuation of the die prior to injection of the molten metal, and may be enclosed in a separate vacuum chamber. One part of the two parts 36a, 36b of the die is fixed, while the other part is movable relative to the one part, for example by a hydraulic assembly (not shown). The dies preferably include ejector pins (not shown) to facilitate ejecting solidified material from the die.

[0068] The die may be composed of various materials, and should have good thermal conductivity, and be relatively resistant to erosion and chemical attack from injection of the molten material. A comprehensive list of possible materials would be quite large, and includes materials such as metals, ceramics, graphite and metal matrix composites. For die materials, we have successfully employed tool steels such as H13 and V57, molybdenum and tungsten based materials such as TZM and Anvilo, copper based materials such as copper beryllium alloy "Moldmax"-high hardness, cobalt based alloys such as F75 and L605, nickel based alloys such as IN 100 and Rene 95, iron base superalloys and mild carbon steels such as 1018. Selection of the die material is critical to producing articles economically, and depends upon the complexity and quantity of the article being cast, as well as on the current cost of the component.

[0069] Each die material has attributes that makes it desirable for different applications. For low cost die materials, mild carbon steels and copper beryllium alloys are preferred due to their relative ease of machining and fabricating the die. Refractory metal such as tungsten and molybdenum based materials are preferred for higher cost, higher volume applications due to their good strength at higher temperatures. Cobalt based and nickel based alloys and the more highly alloyed tool steels offer a compromise between these two groups of materials. The use of coatings and surface treatments may be employed to enhance apparatus...
performance and the quality of resulting parts. The die may also be attached to a source of coolant such as water or a source of heat such as oil (not shown) to thermally manage the die temperature during operation. In addition, a die lubricant may be applied to one or more selected parts of the die and the die casting apparatus. Any lubricant should generally improve the quality of resultant cast articles, and more specifically should be resistant to thermal breakdown, so as not to contaminate the material being injected.

[0070] Molten metal is then transferred from the crucible to the shot sleeve. A sufficient amount of molten metal is poured into the shot sleeve to fill the die cavity and associated runners, biscuit, other cavities. Since IN 718 does not “can” to the extent that titanium alloys do, it is possible to fill the shot sleeve. However, we have produced good quality castings where the sleeve is less than 50% filled, less than about 40% filled, and less than about 30% filled.

[0071] An injection device, such as a plunger 40 cooperates with the shot sleeve 30 and hydraulics or other suitable assembly (not shown) drive the plunger in the direction of arrow 42, to move the plunger between the position illustrated by the solid lines and the position indicated by dashed lines, and thereby inject the molten material from the sleeve 30 into the die cavity 38 (step 50-Fig. 15). In the position illustrated by solid lines, the plunger and sleeve cooperate to define a volume that is substantially greater than the amount of molten material that will be injected. Preferably, the volume is at least twice the volume of material to be injected, more preferably at least about three times. Accordingly, the volume of molten material transferred from the crucible to the sleeve. Where the sleeve is partially filled, any material or skin that solidifies on the sleeve forms only a partial cylinder, e.g., an open curved surface, and is more easily scraped or crushed during metal injection, and reincorporated into the molten material. For injection, we have used plunger speeds of between about 30 inches per second (ips) and 300 ips, and currently prefer to use a plunger speed of between about 50-175 inches per second (ips). The plunger is typically moved at a pressure of at least 1200 psi, and more preferably at least 1500 psi. As the plunger approaches the ends of its stroke when the die cavity is filled, it begins to transfer pressure to the metal. The pressure exerted on the metal is then intensified, preferably to at least 500 psi and more preferably to at least about 1500 psi, to ensure complete filling of the mold cavity. Intensification is also performed to minimize porosity, and to reduce or eliminate any material shrinkage during cooling. After a sufficient period of time has elapsed to ensure solidification of the material in the die, the ejector pins (not shown) are actuated to eject parts from the die (step 52-Fig. 10).

[0072] As is known in the art, articles cast generally and die cast in particular tend to include some porosity, generally up to a few percent. Accordingly, and particularly where such articles are used in more demanding applications, such as compressor airfoils for gas turbine engines, there is a need to reduce and preferably eliminate porosity and otherwise treated as needed (step 54-Fig. 10). The parts are therefore hot isostatically pressed (HIP) as described, above to reduce and substantially eliminate any porosity in the parts as cast. For nickel base superalloys such as IN 718, we prefer to HIP at a temperature of between about 1800-2000 F., more preferably between about 1800-1875 F., for a minimum of about 4 hours, and at a pressure of between about 15-25 ksi.

[0073] If desired, each article may then be heat treated. For airfoils composed of die cast IN 718, the heat treatment includes standard and commercially accepted treatment, such as is disclosed in AMS 5663.

[0074] Actual heat treatment and HIP parameters may be varied depending upon the desired properties and application for the article and target cycle time for the process, however the temperature, pressure and time used during HIP must be sufficient to eliminate substantially all porosity, and homogenize any residual casting segregation but not to allow significant grain growth.

[0075] The parts are inspected (step 56-Fig. 10) using conventional inspection techniques, e.g., by fluorescent penetrant inspection (FPI), radiographic, visual, and after passing inspection may be used or further treated/re-treated if necessary (step 58-Fig. 10).

[0076] As a result of our work with nickel base superalloys, we believe that several conditions are important to produce good quality castings. The melting, pouring and injection of material, particularly for reactive materials, must be performed in a non-reactive environment, and we prefer to perform these operations in a vacuum environment maintained at a pressure preferably less than 100 μm and more preferably less than 50 μm. The amount of superheat should be sufficient to ensure that the material remains substantially and completely molten from the time it is poured until it is injected, but also to enable rapid cooling and formation of small grains once injected. Due to the relatively low superheat, molten metal transfer and injection must be rapid enough to occur prior to metal solidification. The resulting microstructure such as grain size appears to correspond to the sectional thickness of the part being cast as well as the die materials utilized and the superheat used, i.e., thinner sections tend to contain smaller grains and thicker sections (particularly internal portions of thicker sections) tend to include larger grains. Higher thermal conductivity die materials result in articles having smaller grains, as does use of lower superheats. We believe that this results from relative cooling rates of these sections. The rate at which the plunger is moved, and correspondingly the rate at which material is injected into the mold appears to affect the surface finish of the articles as cast, although the design of the gating as well as the die material may also play a role in combination with the injection rate.

[0077] Careful control of the post cast thermal processing is required to fully achieve the benefits offered by the relatively fine as die cast microstructure.

[0078] Die casting provides other significant advantages over forging. The time required to produce a part, from ingot to finished part, is reduced significantly, since there is no need to prepare specially tailored billets of material, and casting broadly is performed in a single step, as opposed to multiple forging operations. In die casting, multiple parts can be produced in a single casting. Die casting enables productivity of parts having complex three dimensional shapes, thereby enabling new software design technology to be applied to and exploited in areas such as gas turbine engines and enabling production of more efficient airfoils.
and other components. We believe that die casting will enable the production of articles having complex shapes utilizing materials that are difficult or impossible to forge into those shapes. Moreover, die cast parts have greater reproducibility than forged or investment cast articles, and can be produced nearer to their finished shape, and with a superior surface finish, which minimizes post forming finishing operations, all of which also reduces the cost of producing such parts.

[0079] While the present invention has been described above in some detail, numerous variations and substitutions may be made without departing from the spirit of the invention or the scope of the following claims. Accordingly, it is to be understood that the invention has been described by way of illustration and not by way of limitation.

What is claimed is:

1. A die cast article composed in weight percent of about 15-25 Cr, 2.5-3.5 Mo, about 5.0-5.75 (Cb +Ta), 0.5-1.25 Ti, 0.25-1.0 Al, up to about 21 Fe, balance generally nickel.

2. The article of claim 1, wherein the article is characterized by a microstructure having an absence of flowlines and having strength, crack growth rates and stress rupture resistance in accordance with AMS 5663.

3. The article of claim 1, wherein the article comprises a gas turbine engine component.

4. The article of claim 3, wherein the article is a compressor component.

5. The article of claim 3, wherein the article is a turbine component.

6. The article of claim 1, wherein the average grain size is smaller than about ASTM 3.

7. The article of claim 1, wherein the article has an ultimate tensile strength at room temperature of at least 180 ksi and a 0.2% yield strength of at least 145 ksi.

8. The article of claim 7, wherein the article has an ultimate tensile strength at about 1200 °F of at least 150 ksi and a 0.2% yield strength of at least 125 ksi.

9. The article of claim 1, wherein the article is characterized by a microstructure having an absence of flowlines and having strength, crack growth rates and stress rupture resistance in accordance with AMS 5663.

10. The article of claim 1, wherein the article has an ultimate tensile strength at room temperature of at least 120 ksi and a 0.2% yield strength of at least 105 ksi.

11. A die cast gas turbine engine component composed in weight percent of about 15-25 Cr, 2.5-3.5 Mo, about 5.0-5.75 (Cb +Ta), 0.5-1.25 Ti, 0.25-1.0 Al, up to about 21 Fe, balance generally nickel.

12. The article of claim 11 characterized by a microstructure with an absence of flowlines.

13. The article of claim 11, wherein the article has room temperature and 1200 F strength and stress rupture resistance in accordance with AMS 5663.

14. The article of claim 11, wherein the article is a compressor component.

15. The article of claim 11, wherein the article is a turbine component.

16. The article of claim 20, wherein the average grain size is smaller than about ASTM 3.

17. The article of claim 11, wherein the article has an ultimate tensile strength at room temperature of at least 180 ksi and a 0.2% yield strength of at least 145 ksi.

18. The article of claim 11, wherein the article has an ultimate tensile strength at about 1200 °F at least 150 ksi and a 0.2% yield strength of at least 125 ksi.

19. The article of claim 11, wherein the article has room temperature and 1200 F strength and stress rupture resistance in accordance with AMS 5383.

20. The article of claim 19, wherein the article has an ultimate tensile strength at room temperature of at least 120 ksi and a 0.2% yield strength of at least 105 ksi.

* * * * *