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(54) Apparatus for die casting material having a high melting temperature

(57) A die casting apparatus for making articles composed of material having a melting temperature in excess of 2000 F, such as superalloys and titanium alloys includes a melting unit 24 for melting at least a charge of the material, and a multi part, die-cavity-defining die 36. A generally cylindrical shot sleeve 30 of the apparatus is in fluid communication with the die 36, and receives molten material from the melting unit 24. The sleeve 30 has outer and inner radii Ro, Ri. The apparatus also includes a plunger unit 40 in sealing and moveable engagement with the shot sleeve 30. The plunger 40 moves along a plunger stroke, for forcing material from the shot sleeve 30 into the die cavity 38. At least the radii and the ratio of the outer to inner radii are selected to minimize thermal distortion of the sleeve when molten material is poured into the sleeve. Preferably the inner radius Ri is at least 25 mm and the ratio Ro/Ri at least 1.3 Preferably, the shot sleeve 30 defines a volume that is at least 2 times the die cavity volume 38.

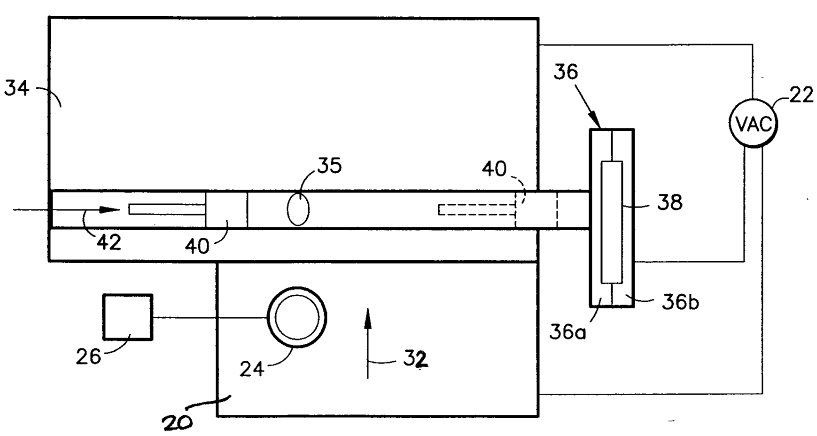

FIG.3

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Description

[0001] The present invention relates generally to die casting, and relates more particularly to apparatus for die casting material having a high melting temperature, e.g., above 2000 °F (1093°C).

[0002] High melting temperature materials, such as nickel base superalloys and titanium base alloys are widely used in a variety of industries. Generally, the term superalloys refers to materials having high strength, particularly at elevated temperatures, e.g., about 900 F and above. Such materials are typically nickel base, cobalt base and/or iron base. Titanium alloys are employed in applications which require light weight and high strength-weight ratios. These alloys exhibit good corrosion resistance, and generally maintain good strength up to moderate temperatures, e.g., up to about 1000°F (538°C).

[0003] In gas turbine engines for example, high melting temperature materials such as nickel base and cobalt base superalloys are typically employed in the turbine section, and sometimes in the later 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 rings, cases and seals. Such materials typically have a melting temperature in excess of 2500 °F (1371°C). One nickel base superalloy widely used in gas turbine engines is Inconel 718 (IN 718), having a general 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)] + Tantalum (Ta)), 0.7 - 1.2 Titanium (Ti), 0.3 - 0.9 Aluminum (Al), up to about 21 Iron (Fe), balance generally Ni, and having a melting temperature of about 2450°F (1343°C).

[0004] Titanium alloys are also employed, typically in cooler sections of the engine such as in the compressor section, including but not limited to airfoils such as blades and vanes, as well as structural components such as intermediate and compressor cases and compressor disks. Titanium alloys generally have a melting temperature in excess of 3000 °F (1649°C). One typical alloy widely utilized in gas turbine engines is Ti-6Al-4V ("Ti 6-4"), which broadly includes about 4 - 8 w/o (weight percent) Al, 3 - 5 w/o V, balance generally Ti. For higher temperature applications, where improved creep properties are needed, Ti 6Al-2Sn-4Zr-2Mo ("Ti 6-2-4-2") may be used, and broadly includes about 5 - 7 w/o Al, about 1.5 - 2.5 w/o Sn (tin), about 3.0 - 5.0 w/o Zr, about 1.5 - 2.5 w/o Mo, balance generally titanium. Other Ti alloys include Ti 8-1-1 and titanium aluminides. Ti 8-1-1 broadly includes about 7-8.5 w/o Al, 0.5-1.5 w/o Mo and 0.5-1.5 w/o V, balance generally titanium. Broadly, titanium aluminides are composed primarily of titanium and aluminum in stoichiometric amounts, such as TiAl and $TiAl_3$. In addition to the above-discussed properties, these materials must at least be capable of being formed into relatively complex, three dimensional shapes such as airfoils, and must be oxidation resistant - particularly at elevated temperatures.

[0005] In the gas turbine engine industry, forging is used to produce parts having complex, three-dimensional shapes such as blades and vanes.

[0006] Briefly, in order to forge a part such as an airfoil, an ingot of material 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 that are shaped progressively similar to the desired shape, in order to plastically deform the material into the desired component shape. The forging dies typically may be heated. Each component is typically heat treated to obtain desired properties, e.g., hardening/strengthening, stress relief, resistance to crack growth and a particular level of HCF resistance, and is also finished, e.g., machined, chem-milled and/or media finished, if necessary to provide the component with the precise shape, dimensions and/or surface features.

[0007] 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. 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 discarded.

[0008] During component forging, much of the original material (up to about 85% depending upon the size of the forging) is removed and does not form part of the finished component, i.e., 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. Some alloys may also exhibit resilient character during forging, which must be taken into account during forging, i.e., the parts must 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 more difficult or impossible to forge titanium alloys precisely into these advanced, more complex shapes, 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 component shapes.

[0009] Forged components may contain forging imperfections that tend to be difficult to inspect. 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 materials 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.

[0010] Casting has been extensively used to produce relatively near-finished-shape articles.

[0011] 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 extremely large grains, e.g., ASTM 0 or larger (relative to the small average grain size achievable by forging), and in some cases the entire part comprises a single grain. 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. If the material is melted, poured and/or solidified in the presence of a gas, parts may have undesirable properties such as inclusions and porosity, particularly for materials containing reactive elements such as titanium or aluminum. Spallation of the ceramic shell also contributes to the presence of inclusions and impurities.

[0012] 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 significant post cast work.

[0013] Die casting, in which molten metal in injected under pressure into a re-usable die, has been used successfully in the past to form articles from materials having relatively low-melting temperatures, e.g., below about 2000 °F (1093°C). 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 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 is oriented horizontally, vertically or inclined between horizontal and vertical. The sleeve typically is constrained at only one end, by the die, e.g., the sleeve is not embedded in a block of material. The sleeve communicates with a runner of the die, and includes an opening on the sleeve through which molten metal is poured. A plunger is positioned for movement in the sleeve, and a driving mechanism moves the plunger and forces molten metal from the sleeve into the die. In a "cold chamber" type die casting machine, the shot sleeve is typically oriented horizontally and is unheated. Casting usually occurs under atmospheric conditions, i.e., the equipment is not located in a non-reactive environment such as a vacuum chamber or inert atmosphere.

[0014] The drawbacks of such machines are discussed, for example in U.S. Pat. No. 3,646,990, particularly in connection with the inability to use such machines to cast materials having higher melting temperatures, e.g., above 2000°F (1093°C). Molten material poured into the shot sleeve occupies and rapidly heats only the lower portions of the sleeve, thereby heating primarily only the bottom of the sleeve. Since the sleeve is constrained at one end, the sleeve distorts or "bows or bananas". This longitudinal distortion along the length of the sleeve, if great enough, prevents movement of the plunger through the sleeve, resulting in damage of the apparatus. Given the necessary, close tolerance between the plunger and sleeve, only a small distortion can result in binding or damage. Such distortion is generally a function of the sleeve outer and inner diameters and length, the material comprising the sleeve, the temperature difference between the molten material and the sleeve, the portion of the sleeve occupied by molten material (causing asymmetrical heating of the sleeve), and the process cycle time (elapsed time between pours of molten alloy into the shot sleeve). It has generally accepted, see e.g., the '440 and '990 patents, that such distortion is the major reason that cold chamber type apparatus cannot be used to cast materials having a high melting temperature - above about 2000 °F (1093°C).

[0015] Thermal distortion also affects the cross sectional shape of the sleeve. As noted above, the sleeve is formed with a generally cylindrical shape, and thus has a circular cross section (in a direction viewed normal to the sleeve length). When molten material is poured into the sleeve, the lower portion of the sleeve (in contact with the molten material) expands relative to the upper, less heated portion of the sleeve. The sleeve distorts such that the cross sectional shape of the sleeve becomes somewhat oval (including a portion that becomes smaller than an unheated sleeve) while the plunger remains more cylindrical, exhibiting less thermal distortion. Accordingly, the sleeve shape and plunger shape fail to match, and where the mismatch is sufficiently great the plunger binds in the sleeve or permits molten alloy to pass between the plunger and shot sleeve - referred to as "blowby", with resulting inoperative or damaged apparatus. Cross sectional distortion is a function generally of the same factors set forth above with respect to banana-ing of the sleeve.

[0016] Moreover, where the shot sleeve is unheated or is heated but maintained at a temperature below the melting temperature of the material being injected, 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 of 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.

[0017] In sum, conventional "cold chamber" die casting apparatus have not been used successfully to produce articles composed of high melting temperature materials, e.g., T_m above about 2000 °F (1093°C), such as superalloys and titanium alloys. As suggested by the '990 patent, use of conventional apparatus results in inoperative and/or broken die casting machinery, as well as articles characterized by inferior qualities such as impurities (e.g., due to solidified material that is injected with the molten material), unacceptable levels of porosity, and relatively poor strength and low and high cycle fatigue properties.

[0018] It is an object of the present invention to provide an apparatus for die casting articles composed of high melting temperature materials, such as nickel base, cobalt base and iron base superalloys and titanium alloys.

[0019] It is still another object of the present invention to provide an apparatus for casting articles having complex, three dimensional shapes are difficult if not impossible to forge.

[0020] According to one aspect of the invention, an apparatus for die casting articles composed of a high melting temperature material (T_m at least 2000° F (1093°C)) and/or a reactive alloy is disclosed. The apparatus utilizes a reusable die defining a die cavity and including at least two parts. A melting unit of the apparatus melts at least a single charge of metal, e.g., a sufficient amount to fill the die cavity and associated runner(s) and sprue(s). The apparatus also includes a length of generally horizontal, shot sleeve that is coupled to the die and has a cylindrical shape with an inner and an outer radius. The shot sleeve is preferably selected to have a volume greater than at least twice, and preferably three times, the volume of the die cavity (which includes volume such as the associated runners, gating and biscuit), and is typically fabricated from a material such as hardened H13 tool steel. In some instances it may be acceptable for shot sleeve volume to be equal to or slightly greater than the volume of the die cavity.

[0021] The sleeve preferably has a ratio of outer to inner radii (Ro/Ri) of at least about 1.3 and more preferably about 1.5. Such a combination provides adequate volume of molten material, but also sufficiently minimizes the tendency of the sleeve to thermally distort - bow along its length and ovalize in cross section - when partially filled with molten material, thereby preventing machine jamming. A plunger assembly of the apparatus is included for injecting molten material from the shot sleeve into the die, as is a transfer device for transferring molten metal from the melting unit to the shot sleeve.

[0022] Exemplary high melting temperature alloys include titanium alloys (T_m typically above about 3000°F (1649°C) and cobalt base and nickel base superalloys (T_m typically above about 2400°F (1315°C)). Exemplary reactive alloys include titanium alloys and superalloys (T_m typically above about 2400°F (1315°C).

[0023] The present invention is advantageous in that it enables the die casting of high melting temperature materials using conventional die casting machinery which was previously believed to be incapable of use in casting high melting temperature materials.

[0024] A preferred embodiment of the present invention will now be described, by way of example only, with reference to the accompanying drawings in which:

[0025] FIG. 1 illustrates an article die cast using the apparatus of the present invention.

[0026] FIGS. 2 and 3 are schematic views of a die casting machine in accordance with the present invention.

[0027] FIG. 4 is a sectional view of a shot sleeve of the apparatus of FIG. 2 taken along the line 5-5, illustrating the distortion of the cross section of the sleeve.

[0028] FIG. 5 is a chart illustrating the deflection of the shot sleeve when partly filled with molten metal as a function of the sleeve inner and outer radii.

[0029] FIG. 6 is a chart similar to FIG. 5 and illustrating the tendency of the sleeve cross section to distort as a function of the sleeve inner and outer radii.

[0030] Turning now to FIG. 1, a superalloy article composed of high melting temperature material and in die cast in accordance with the present invention is indicated generally by the reference numeral 10. In the illustrated embodiment, the article is a turbine blade 10 for a gas turbine engine, and includes an airfoil 12, a platform 14, and a root 16. As used herein, high melting temperature materials refers to those materials having a melting temperature of at least about 2000°F (1093°C), and as high as 3000°F (1649°C) and higher. The present invention is broadly applicable to high melting temperature materials such as nickel base, cobalt base and iron base superalloys and titanium base alloys used for various applications, and is not intended to be limited to any particular superalloy or to gas turbine engine parts.

[0031] As noted above, a typical nickel base superalloy utilized in gas turbine engines is Inconel 718 (IN 718), which broadly has a composition in weight percent, of 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. IN 718 has a melting temperature of about 2450°F (1343°C). Other alloys may also be employed, such as IN 713 having a nominal composition in weight percent, of up to about 0.025 Carbon (C), up to about 0.4 Manganese (Mn), up to about 0.4 Silicon (Si), 12 - 16 Chromium (Cr), 3 - 6 Molybdenum (Mo), 0.8 - 3.5 (Columbium (Cb) + Tantalum (Ta)), 0.7 - 1.3 Titanium (Ti), 5.25 - 6.75 Aluminum (Al), up to about 1 Iron (Fe), balance essentially Ni and Cobalt (Co). IN 713 has a melting temperature of about 2300°F (1260°C). Waspaloy is another material useful for such applications, and is disclosed for example in U.S. Pat. Nos. 4,574,015 and 5,120,373. Generally, Waspaloy has a composition in weight percent, of about 0.02 - 0.15 Carbon (C), 12 - 20 Chromium (Cr), 10 - 20 Cobalt (Co), 2 - 5.5 Molybdenum (Mo), 3 - 7 Titanium (Ti), 1.2 - 3.5 Aluminum (Al), 0.01 - 0.15 Zirconium (Zr), 0.002 - 0.05 Boron (B), balance essentially Ni. Waspaloy has a melting temperature of about 2400°F (1315°C).

[0032] Other alloys include B-1900, which has a nominal composition of about 8 Cr, 10 Co, 6 Mo, 4 Ta, 6 Al, 1 Ti, 0.1 C, 0.015 B, and 0.1 Zr. See, e.g., Sims and Hagel, The Superalloys, (Wiley & Sons 1972), pp. 596-7. Cobalt base alloys, such as MAR-M-509 are also used in higher temperature applications. MAR-M-509 has a nominal composition, in weight percent, of about 23.5 Chromium (Cr), 10 Nickel (Ni), 7 Tungsten (W), 3.5 Tantalum (Ta), 0.2 Titanium (Ti), 0.5 Zirconium, balance essentially Cobalt. See, e.g., U.S. Pat. No. 3,647,517 and Sims and Hagel, *The Superalloys,* (Wiley & Sons 1972), pp. 596-7. IN 939 is another nickel base alloy, useful up to about 1500 F, and has a nominal composition of about 22.5 Cr, 19 Co, 6 Mo, 2 Al, 3.7 Ti, 2 W, 3.3 (Cb + Ta), 0.15 C, 0.005 B, balance generally nickel. Gatorized Waspaloy is an advanced Waspaloy composition developed to provide improved strength and temperature capability over conventional Waspaloy. See, U. S. Pat. Nos. 4,574,015 and 5,120,373. It has a general composition, in weight percent of Chromium 15 .00 - 17 .00, Cobalt 12 .00- 15 .00, Molybdenum 3 .45- 4 .85, Titanium 4 .45- 4 .75, Aluminum 2 .00- 2 .40. Gator Waspaloy may also small amounts of other elements such as Zirconium 0 .02- 0 .12, Boron 0 .003- 0 .010, and Magnesium 0 .0010- 0 .005.

[0033] As also note above, titanium alloys are also employed, and generally have a melting temperature in excess of 3000°F (1649°C). One typical alloy widely utilized in gas turbine engines is Ti 6Al-4V ("Ti 6-4"), which broadly includes about 4 - 8 w/o (weight percent) Al, 3 - 5 w/o V, balance generally Ti. For higher temperature applications, where improved high temperature properties are needed, Ti 6Al-2Sn-4Zr-2Mo ("Ti 6-2-4-2") may be used, and broadly includes about 5 - 7 w/o Al, about 1.5 - 2.5 w/o Sn (tin), about 3.0 - 5.0 w/o Zr, about 1.5 - 2.5 w/o Mo, balance generally titanium. Other Ti alloys include Ti 8-1-1 and titanium aluminides. Ti 8-1-1 broadly includes about 7-8.5 w/o Al, 0.5-1.5 w/o Mo and 0.5-1.5 w/o V, balance generally titanium. Broadly, titanium aluminides are composed of stoichiometric amounts of titanium and aluminum, and have exemplary compositions of TiAl and TiAl3.

[0034] Turning to FIGS. 2 and 3, the apparatus of the present invention is indicated generally by the reference numeral 18. Where high quality die cast articles must be prepared, it is important to melt the materials in a non-reactive environment so as to prevent reaction, contamination or other condition which might detrimentally affect the quality of the resulting articles. Since any gasses 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 low pressure, e. g., less than 100 μm Hg and more preferably less than 50 μm Hg.

[0035] We prefer to melt single charges of material, since it is generally quicker to melt smaller amounts of material than larger amounts and since the melting equipment associated with melting smaller charges of material is more readily located in a vacuum chamber. Particularly where the material contains reactive elements, we prefer to melt the high melting temperature material by induction skull remelting or melting (ISR) 24, for example in a unit of the type manufactured by Consarc Corporation of Rancocas, NJ which is capable of rapidly, cleanly melting a single charge of material to be cast, e.g., up to about 50 pounds (22.7 kg) 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 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 skull. 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, further reducing attack of the crucible wall by the molten material.

[0036] 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 enabling formation of small grains and also to minimize the thermal load upon the die casting apparatus (particularly those portions of the apparatus which come into contact with the molten metal). As a general rule, we prefer to limit the superheat for high melting temperature materials to within about 200 °F (111°C) over the melting point, more preferably less than 100 °F (55°C), and most preferably less than 50 °F (28°C). We have found that the process of pouring and injecting the molten material in one or two seconds works well in a die casting machine having an unheated shot sleeve.

[0037] While we prefer to charges of material using an ISR unit, the material may be melted in other manners, such as by vacuum induction melting (VIM) and electron beam melting, so long as the material being melted is not significantly contaminated. Moreover, we do not rule out melting bulk material, e.g., multiple 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, where 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 affecting the cycle time.

[0038] In order to transfer molten material from the crucible to a shot sleeve 30 of the apparatus, the crucible is mounted for translation (arrow 32 of FIG. 3), and also for pivotal movement (arrow 33 of FIG. 2) about a pouring axis, and in turn is mounted to a motor (not shown) for rotating the crucible to pour molten material from the crucible through a pour hole 35 of the shot sleeve 30. Translation of the crucible 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 with a pressure level less than 100 μm and more preferably less than 50 μm. The melt chamber 20 and pour chamber 34 may be 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. While the illustrated embodiment includes separate melting and pouring chambers, it is also possible to perform melting and pouring in a single chamber. We prefer to use separate chambers in order to minimize the loss of vacuum environment in the event that a given component must be exposed to atmosphere, e.g., to service the melting unit or the shot sleeve or to remove a casting.

[0039] The sleeve 30 is typically fabricated from hardened H13 tool steel. We have determined that the above noted problem of thermal distortion of the shot sleeve can be obviated to the extent necessary to enable such a die casting machine to be used in the casting of materials which are molten at temperatures in excess of 2000°F (1093°C) and even 3000°F (1649°C). Such use depends largely upon the relationship between the inner and outer radii. As indicated in FIG. 4, the sleeve when cylindrical, e.g., cool, has an inner radius Ri and an outer radius Ro. As molten material is poured into the lower portion of the sleeve, the lower portion expands relative to the upper portion and distorts or essentially "ovalizes" the sleeve, as indicated by the dashed lines. The resulting oval (non-cylindrical) shape can be characterized generally by major and minor axes Ma and Mm, respectively. Excessive ovalization of the shot sleeve, and longitudinal distortion of the sleeve (indicated by dashed lines in FIG. 2), are the primary reasons that such apparatus have not previously been use to die cast high melting temperature materials. Sleeve parameters and design which enable such die casting are discussed below.

[0040] The shot sleeve is preferably selected to have a volume greater than at least twice, and preferably at least three times, the volume of the die cavity (including the excess volume, such as the runners and biscuit associated with the casting). For a given volume of material to be injected, the use of a sleeve having smaller inner (and outer) radii necessitate the use of longer plunger strokes (and thus longer injection times), since for a cylinder volume is related to plunger stroke/length generally by the relationship volume = n x R_i^2 x stroke/length. The sleeve preferably has a ratio of outer to inner radii (Ro/Ri) of at least about 1.3 and more preferably about 1.5. We have determined that such a combination provides adequate volume of molten material, yet sufficiently minimizes the tendency of the sleeve to thermally distort (indicated by the dashed lines in FIG. 2) - bow along its length and ovalize in cross section (FIG. 4) - particularly when only partially filled with molten material, thereby preventing machine jamming. Surprisingly, it is the above combination which enables such a machine to be used in the die casting of high melting temperature materials, e.g., superalloys and titanium alloys, and importantly to do so in a cost effective manner. Development work conducted on a prototype machine using pour weights of approximately 7 pounds (3.2 kg) of titanium indicate that a preferred inner radius of at least 1.5 inches (38 mm) and a preferred outer radius of at least 2.25 inches (57 mm). While the above sleeve dimensions are preferred for the melt weight evaluated, the sleeve geometry can be generalized for a critical ratio of sleeve radii for a broad range of melting and pouring weights. Smaller sleeve dimensions can be used, e.g., inner diameters of less than 1.5 inches (38 mm), but the sleeve fill level needs to remain below about 50 %, particularly in the case of titanium in order to avoid canning. While the sleeve 30 is illustrated as unheated, the sleeve may have attached heating elements (not shown) for the purpose of maintaining the sleeve at some desired, minimum temperature, to reduce the induced thermal shock when molten material is poured into the sleeve or to thermally balance the sleeve. Conversely, the shot sleeve may be cooled to remove heat and maintain lower temperatures. In some instances, dual material sleeves or composite sleeves may be used to maintain thermal balance.

[0041] As noted above, the molten material is transferred from the crucible 24 into the shot sleeve 30 through a pour hole 35. 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.

[0042] The illustrated die 36 includes two sections, 36a, 36b, (but may include more sections) which cooperate to define the die cavity 38, for example in the form of a compressor blade or vane for a gas turbine engine. The die 36 is also preferably coupled directly to the vacuum source and also through the shot sleeve, to enable evacuation of the die prior to injection of the molten metal. The die may also be located in a vacuum chamber. One section of the two sections 36a, 36b of the die is typically fixed, while the other part is movable relative to the one section, for example by a hydraulic assembly (not shown). The die preferably includes ejector pins (not shown) to facilitate ejecting solidified material from the die. The die may also include a stripper mechanism (not shown) for removing casting material from the die while the material is still hot, to further reduce thermal loads on the die and reduce solidification shrinkage stresses on the casting.

[0043] The die may be composed of various materials, and should have good thermal conductivity (to enable rapid solidification of the molten material and resulting fine grains), 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, ceramic matrix composites 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 Anviloy, copper based materials such as copper beryllium alloy "Moldmax"- high hardness, cobalt based alloys such as F75 and L605, nickel-iron based alloys such as IN 100 and Rene 95, iron base superalloys such as IN 718 and mild carbon steels such as 1018 and 1030. 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.

[0044] 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 metals 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.

[0045] Molten metal is transferred from the crucible 24 to the shot sleeve 30. A sufficient amount of molten metal is poured into the shot sleeve to only partially fill the sleeve, but subsequently to fill the die. As previously discussed and as indicated in FIG. 4, the sleeve is preferably less than 50% filled (indicated generally by the dashed line 50), more preferably less than about 40% filled (indicated by the broken line 52), and most preferably less than about 30 - 33% filled (dotted line 54). In some instances, e.g., IN 718 it may be acceptable to completely fill the sleeve.

[0046] An injection device, such as a plunger 40 cooperates with the shot sleeve 30 and hydraulics or other suitable assembly (not shown) to drive the plunger in the direction of arrow 42, to move the plunger between the position illustrated by the solid lines and the position 40' indicated generally by dashed lines, and thereby inject the molten material from the sleeve 30 into the die cavity 38. 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, as noted above. Since the sleeve is only partially filled, any material or skin that solidifies on the sleeve forms only a partial cylinder, e.g., an open arcuate surface, and is easily scraped or crushed during metal injection, and reincorporated into the molten material. For some materials, there is a sufficiently large solidification range so that skin formation is minimized, and it possible to more completely fill the sleeve.

[0047] Turning to FIGS. 5 and 6, we have determined that the relationship between outer and inner radii, as well as the radii themselves are critical to enabling a conventional cold chamber type die casting machine to be used to produced parts from high melting temperature materials. FIGS. 5 and 6 are based upon a molten material temperature of about 3100°F (1704°C) and a sleeve fill of about 25 %. FIG. 5 illustrates the relationship between the outer and inner radii (Ro/Ri) to the tendency of a shot sleeve to deflect along its length, referred to above as longitudinal distortion or "banana-ing" and illustrated by the dashed lines for the sleeve in FIG. 2). In general, less longitudinal distortion or banana-ing corresponds to a reduced likelihood of jamming. As the ratio of the outer radius to inner radius approaches 1.0, e.g., the shot sleeve has a thinner wall, the deflection of a partially filled shot sleeve increases dramatically. As the ratio exceeds about 2.0 the deflection tends to be relatively small, on the order of less than about 0.005 inch (0.127 mm). If this deflection is too great, which we believe occurs at a deflection greater than about 0.005 inch (0.127 mm) (for a 12 inch (305 mm) sleeve), then the plunger jams in the sleeve over the course of its plunger stroke, and renders the machine inoperative.

[0048] As indicated in FIGS. 5 and 6, for a sleeve having an inner radius of about 1 inch (25 mm), we prefer that the ratio of outer to inner radii be at least about 1.3, with the outer radius being at least about 1.3 inches (33 mm). For a sleeve having an inner radius of about 1.5 inches (38 mm), we prefer that the ratio of outer to inner radii be at least about 1.3, and more preferably about 1.5 with the outer radius being at least about 2.25 inches (57 mm). For a sleeve having an inner radius of about 2 inches (51 mm), we prefer that the ratio of outer to inner radii be at least about 1.7, with the outer radius being at least about 3.4 inches (86 mm). While it is apparent from our work that use of shot sleeves with small inner radii (< than 1 inch (25 mm)) leads to more distortion resistant shot sleeves, the use of these smaller sleeves must be balanced against the need to control shot sleeve fill levels in order to minimize shot sleeve "canning". Accordingly, we prefer that the ratio of outer to inner radii lie to the right of the "knee" for each respective curve. Accordingly, we prefer that the ratio of outer to inner radii lie to the right of the "knee" for each respective curve.

[0049] FIG. 6 illustrates the relationship between the outer and inner radii (Ro/Ri) to the tendency of a shot sleeve to ovalize when the sleeve is partially filled with molten material, e.g., the tendency of the cylindrical cross section to become non-circular or oval when the sleeve is partially filled and molten material rests along the lower portion of the sleeve. As the ratio of the outer radius to inner radius approaches 1.0, the sleeve distortion or ovalization upon being partially filled (less than about 50% filled) increases dramatically. As the ratio exceeds about 2.0 the distortion tends to be relatively small, on the order of less than about 1.5 percent which again occurs at about the knee of each curve. As molten material fills the lower portion of the sleeve, the lower portion expands more than does the upper portion, in effect ovalizing the shot sleeve, which can be characterized generally as having a major axis slightly greater than the original dimension (radius) and a minor axis slightly smaller than the original dimension (radius). If this ovalization is too great, i.e., the minor axis becomes smaller than the plunger radius, the cylindrical plunger will jam in the ovalized sleeve or the material will pass between the plunger and the sleeve ("blow by"), rendering the machine inoperative. Accordingly, we prefer that the ratio of outer to inner radii lie to the right of the "knee" for each respective curve. For a sleeve having an inner radius of about 1 inch (25 mm), we prefer that the ratio of outer to inner radii be at least about 1.3, with the outer radius being at least about 1.3 inches (33 mm). For a sleeve having an inner radius of about 1.5 inches (38 mm), we prefer that the ratio of outer to inner radii be at least about 1.3, and more preferably about 1.5 with the outer radius being at least about 2.25 inches (57 mm). For a sleeve having an inner radius of about 2 inches (51 mm), we prefer that the ratio of outer to inner radii be at least about 1.5, with the outer radius being at least about 3 inches (76 mm).

[0050] The sleeve must resist both longitudinal distortion and also ovalization. In addition, the sleeve must have a volume that is sufficient to receive material while (preferably) being less than about 33% filled, and the plunger stroke cannot be too long (injection would take too long and molten material in the sleeve would solidify). Accordingly, for die casting articles such as blades and vanes (with a charge of about 7 pounds (3.2 kg) of Ti 6-4 material, for example) we have used a compromise between these considerations is the use of a sleeve having an inner radius of about 1.5 inches (38 mm) with a ratio of outer to inner radii of about 1.5.

[0051] The die casting apparatus of the present invention provides significant advantages. The present invention enables the use of "cold chamber" type die casting machines to be used to produce articles composed of high melting temperature materials, e.g., Tm in excess of 2000°F (1093°C) and even 3000°F (1649°C). The present invention enables the die casting of such materials. Moreover, multiple parts can be produced in a single casting, thereby reducing cost of producing each part.

[0052] 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.

Claims

1. A die casting apparatus for making articles composed of material having a melting temperature in excess of 2000°F, the apparatus comprising:

   a melting unit (24) for melting at least a single charge of the material;
   a multi part, die-cavity-defining die (36);
   a generally cylindrical shot sleeve (30) in fluid communication with the die (36) and for receiving molten material from the melting unit (24), the sleeve having outer (Ro) and inner (Ri) radii; and
   a plunger unit (40) in sealing and moveable en-

gagement with the shot sleeve (30) along a plunger stroke for forcing material from the shot sleeve (30) into the die cavity (36); wherein for a given sleeve inner radius Ri at least the radii (Ri, Ro) and the ratio of the outer to inner radii (Ro/Ri) are selected to minimize thermal distortion of the sleeve (30) when molten material is poured into the sleeve.

2. The apparatus of claims 1, wherein the thermal distortion comprises a deflection of the cylinder along its length and a distortion of the cylindrical cross section of the sleeve.

3. The apparatus of claims 1 or 2, further comprising:
means (22) for providing a reduced pressure environment for the melting unit (24), the die (36) and the shot sleeve (30).

4. The apparatus of claim 3, wherein the reduced pressure means separately provides reduced pressure environments for the melting unit (24), the die (36) and the shot sleeve (30).

5. The apparatus of any preceding claim, wherein the material has a melting temperature in excess of 3000 °F.

6. The apparatus of any preceding claim, wherein the inner radius (Ri) is at least 1 inch (25 mm).

7. The apparatus of any preceding claim, wherein the ratio (Ro/Ri) is at least 1.25.

8. The apparatus of claim 7, wherein the ratio (Ro/Ri) is at least 1.5.

9. The apparatus of claim 8, wherein the inner radius (Ri) is at least about 1.5 inches (38 mm).

10. The apparatus of any preceding claim, wherein the die (36) is composed of material selected from the group consisting of mild carbon steels, copper beryllium alloys, tungsten base alloy, cobalt base alloys and molybdenum base alloys.

11. The apparatus of any preceding claim, wherein the shot sleeve (30) is composed of H13 tool steel.

12. The apparatus of any preceding claim, wherein the die (30) defines a die cavity volume (38), and the shot sleeve (30) defines a volume that is at least about 2 times the volume of the die cavity (36).

13. The apparatus of any preceding claim, further comprising:
means for controlling the temperature of the shot sleeve.

14. A generally cylindrical shot sleeve (30) for a die casting apparatus, the sleeve (30) having an inner radius Ri of at least 25 mm and a ratio of outer radius Ro to inner radius Ri of at least 1.3.

15. A method of die casting a high temperature melting point material with apparatus comprising a cylindrical shot sleeve (30) having an inner radius (Ri) and an outer radius (Ro) wherein the radii (Ro and Ri) and the ratio Ro/Ri are selected such that the longitudinal deflection of the shot sleeve (30) is maintained below about 0.005 inches (0.13 mm) and/or the ovalisation of the sleeve (30) is maintained below about 1.5%.

FIG.1

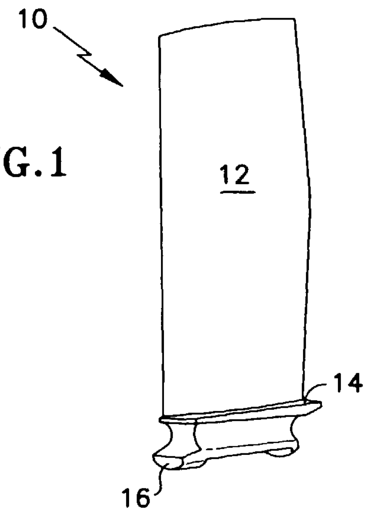
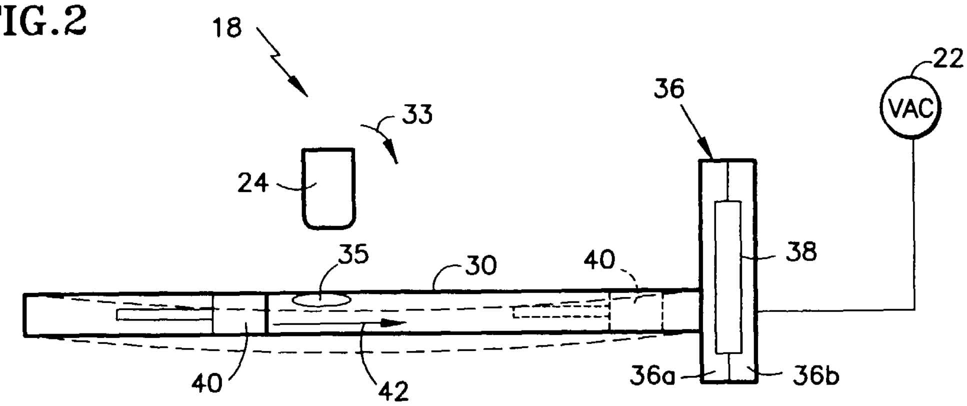


FIG.2



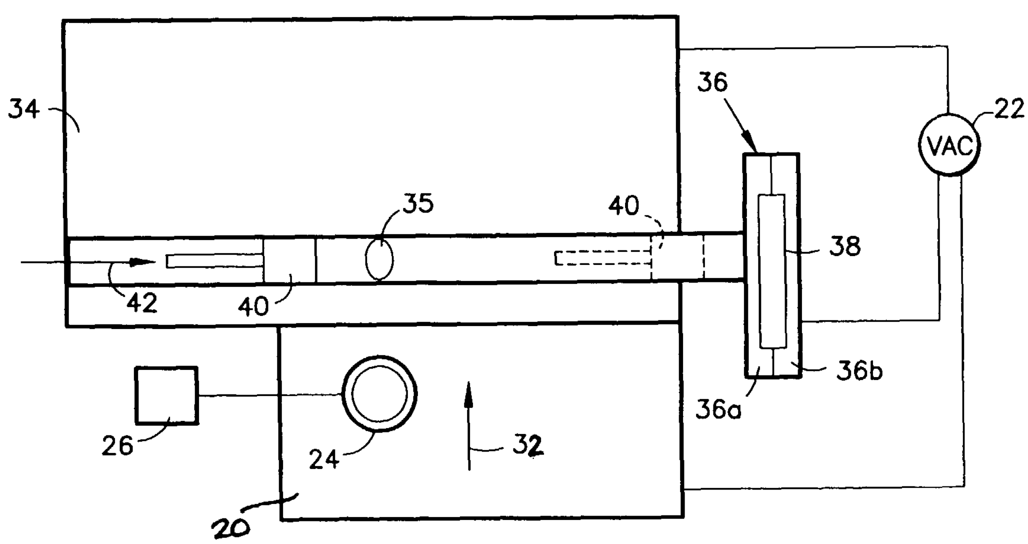
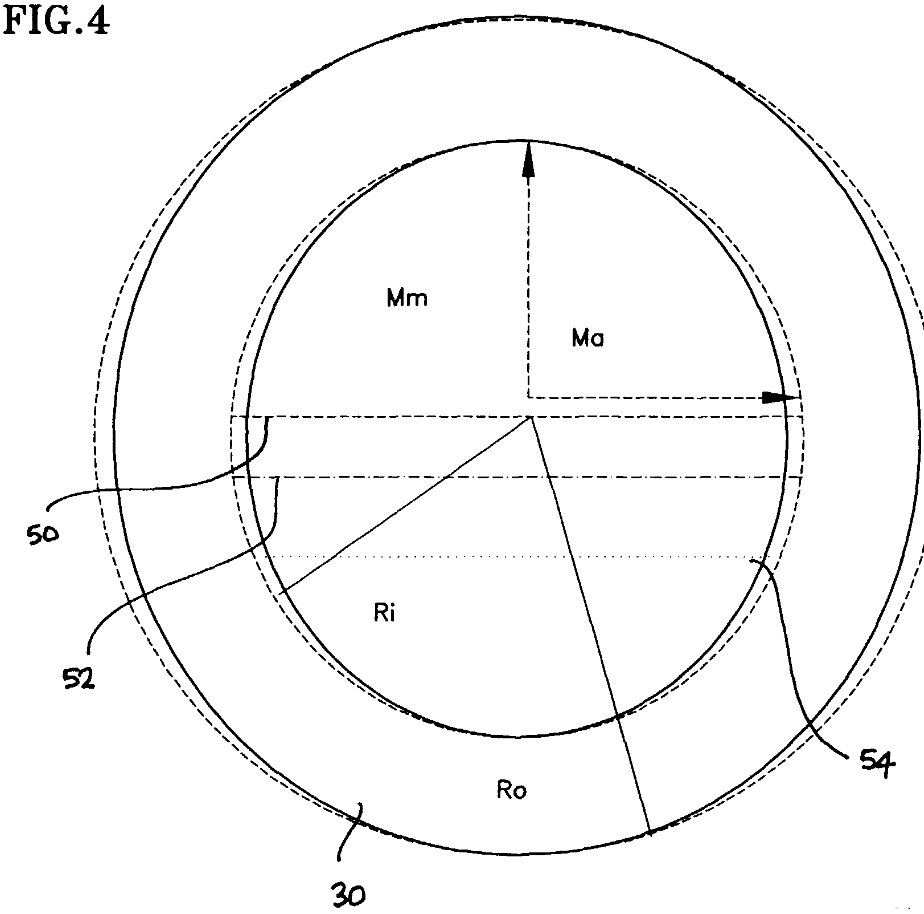


FIG.3

FIG.4



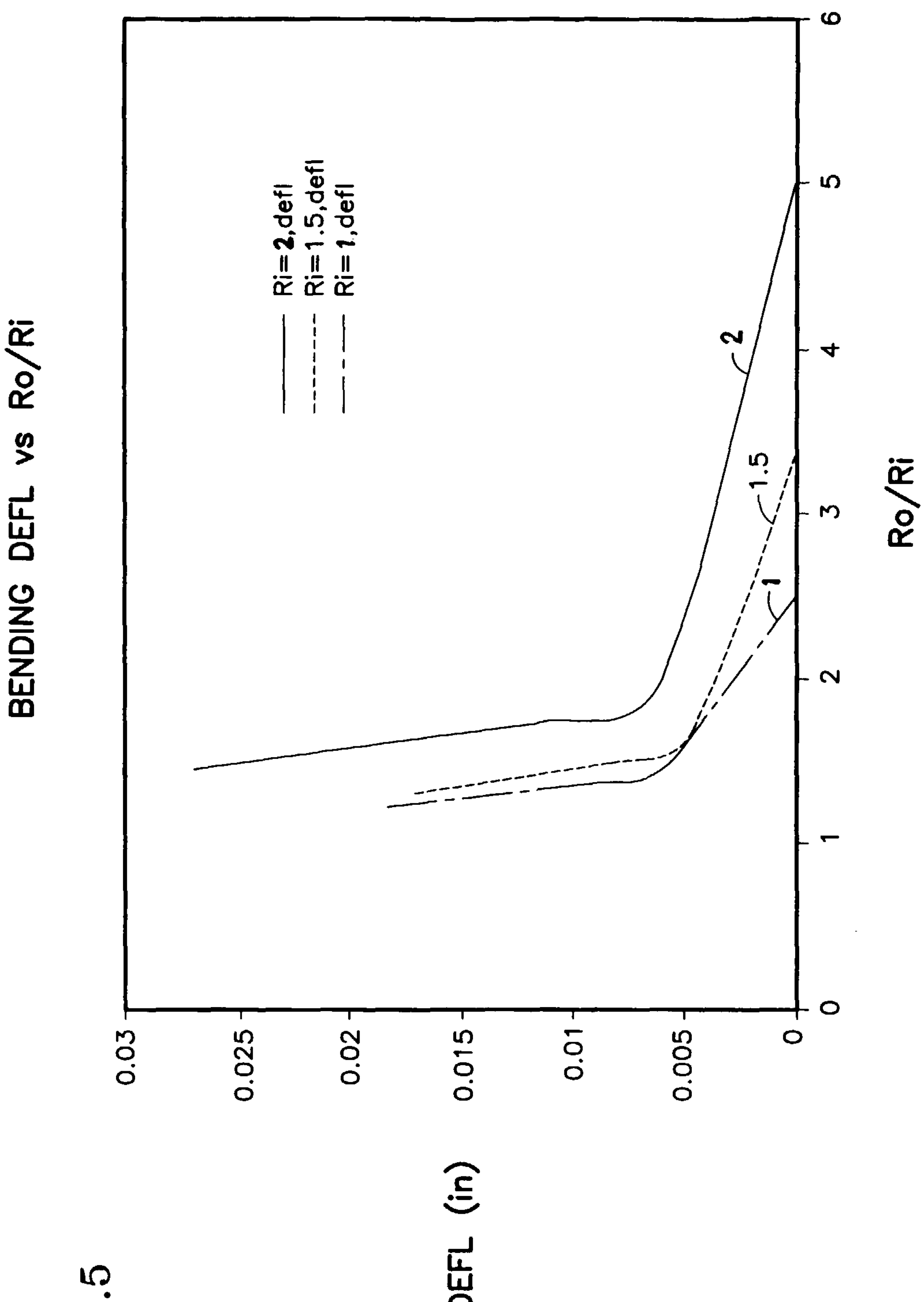
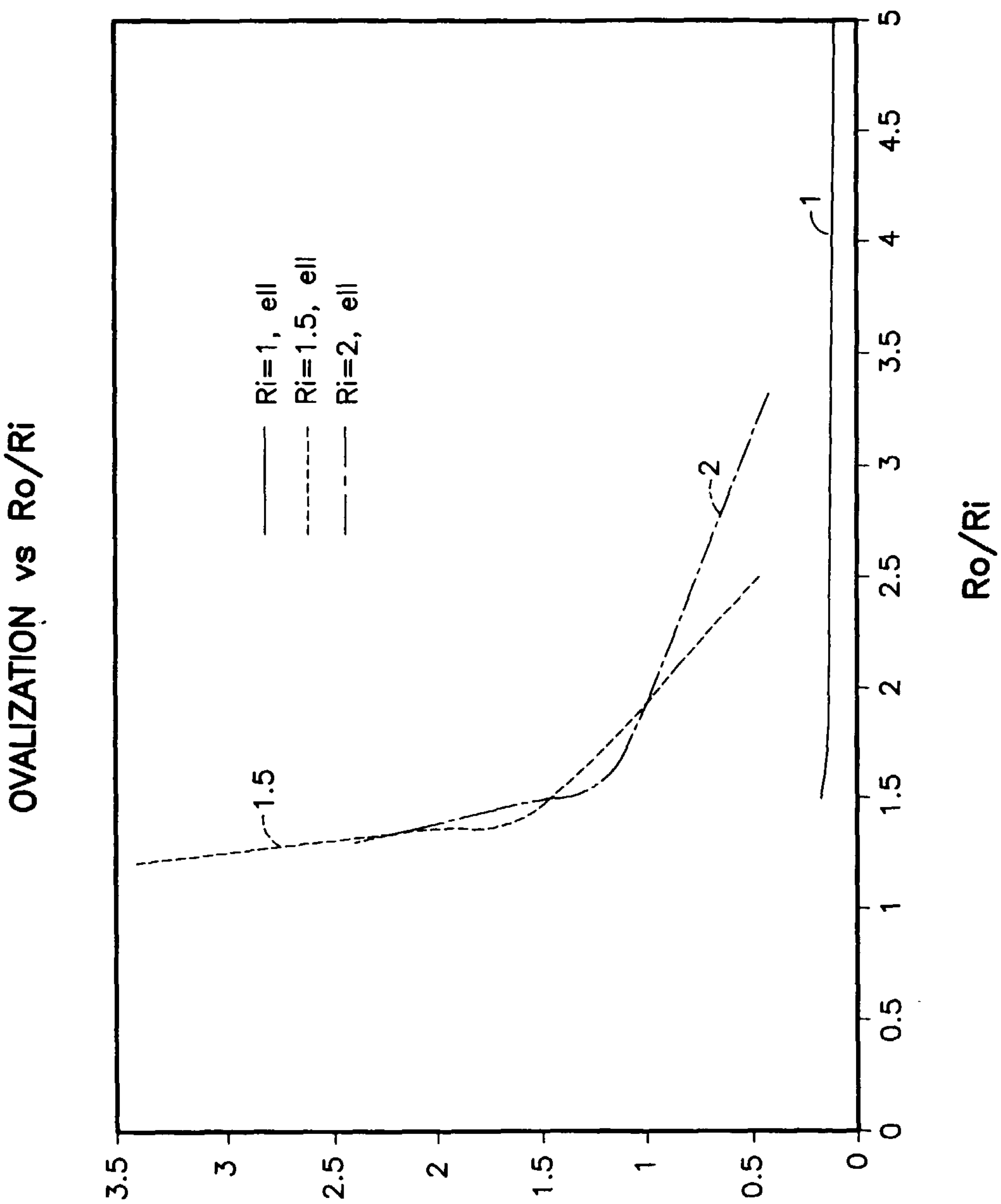

BENDING DEFL vs Ro/Ri
DEFL (in)
0.03
0.025
0.02
0.015
0.01
0.005
0
Ro/Ri
0
1
2
3
4
5
6
Ri=2,defl
Ri=1.5,defl
Ri=1,defl
2
1.5
1

FIG.5

FIG.6


OVALIZATION vs Ro/Ri
Ri=1, ell
Ri=1.5, ell
Ri=2, ell
1.5
2
1
ELLIPTICITY
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Ro/Ri

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EUROPEAN SEARCH REPORT

Application Number
EP 99 31 0240

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Place of search	Date of completion of the search	Examiner
BERLIN	10 April 2000	Kesten, W

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