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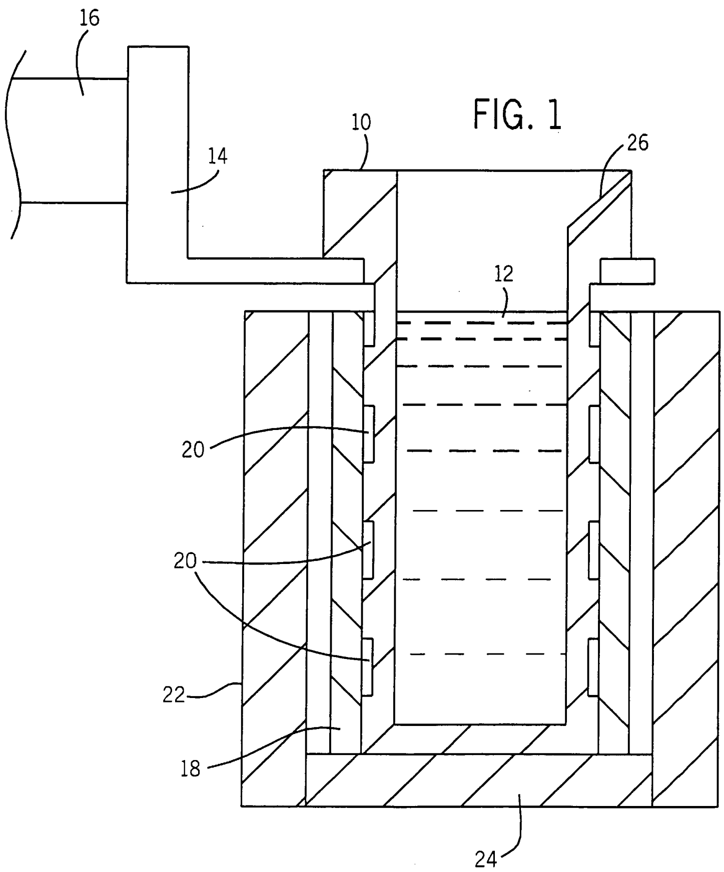
(71) Applicant: **BRUNSWICK CORPORATION**
Lake Forest, Illinois 60045 (US)

(72) Inventor: **Kopper, Adam, E.**
Oshkosh
WI 54904 (US)

(74) Representative: **Gesthuysen, von Rohr & Eggert**
Patentanwälte
Huyssenallee 100
45128 Essen (DE)

(54) Semi-solid casting method and charge

(57) A semi-solid casting method for casting a solid-fraction alloy, comprising heating said alloy to a molten liquid state, cooling and stirring said alloy to nucleate and create a partial solid phase of said solid-fraction, and transferring said alloy while in said partial solid phase of said solid-fraction to a casting machine, characterized in that the method is used with a low-solid-fraction, namely 10 to 30% solid-fraction, alloy.



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Description

[0001] The invention relates to a slurry-on-demand (SOD) casting method according to the preamble of claim 1 and to a SOD casting alloy charge according to the preamble of claim 7.

[0002] The present invention relates in general to producing an "on-demand" semi-solid material for use in a casting process. The prior art forming the starting point of the invention (WO-A-O1/91945) incorporates electromagnetic stirring and various temperature control and cooling control techniques and apparatuses to facilitate the production of the semi-solid material within a comparatively short cycle time. Also included are structural arrangements and techniques to discharge the semi-solid material directly into a casting machine shot sleeve.

[0003] As used herein, the concept of "on-demand" means that the semi-solid material goes directly to the casting step from the vessel where the material is produced. The semi-solid material is typically referred to as a "slurry" and the slug which is produced as a "single shot" is also referred to as a billet. These terms have been combined in its disclosure to represent a volume of slurry which corresponds to the desired single shot billet.

[0004] Semi-solid forming of light metals for net-shape and near-net shape manufacturing can produce high strength, low porosity components with the economic cost advantages of die casting. However, the viscosity of semi-solid metal is very sensitive to the slurry's temperature or the corresponding solid fraction. In order to obtain good fluidity at high solid fraction, the primary solid phase of the semi-solid metal should be nearly spherical.

[0005] In general, semi-solid processing can be divided into two categories; thixocasting and rheocasting. In thixocasting, the microstructure of the solidifying alloy is modified from dendritic to discrete degenerated dendrite before the alloy is cast into solid feedstock, which will then be re-melted to, a semi-solid state and cast into a mold to make the desired part. In rheocasting, liquid metal is cooled to a semi-solid state while its microstructure is modified. The slurry is then formed or cast into a mold to produce the desired part or parts.

[0006] The major barrier in rheocasting is the difficulty to generate sufficient slurry within preferred temperature range in a short cycle time. Although the cost of thixocasting is higher due to the additional casting and remelting steps, the implementation of thixocasting in industrial production has far exceeded rheocasting because semi-solid feedstock can be cast in large quantities in separate operations which can be remote in time and space from the reheating and forming steps.

[0007] In a semi-solid casting process, generally, a slurry is formed during solidification consisting of dendritic solid particles whose form is preserved. Initially, dendritic particles nucleate and grow as equiaxed dendrites within the molten alloy in the early stages of slurry or semi-solid formation. With the appropriate cooling rate and stirring, the dendritic particle branches grow larger and the dendrite arms have time to coarsen so that the primary and secondary dendrite arm spacing increases. During this growth stage in the presence of stirring, the dendrite arms come into contact and become fragmented to form degenerate dendritic particles. At the holding temperature, the particles continue to coarsen and become more rounded and approach an ideal spherical shape. The extent of rounding is controlled by the holding time selected for the process. With stirring, the point of "coherency" (the dendrites become a tangled structure) is not reached. The semi-solid material comprised of fragmented, degenerate dendrite particles continues to deform at low shear forces. The present invention incorporates apparatuses and methods in a novel and unobvious manner which utilize the metallurgical behavior of the alloy to create a suitable slurry within a comparatively short cycle time.

[0008] When the desired fraction solid and particle size and shape have been attained, the semi-solid material is ready to be formed by injecting into a die-mold or some other forming process. Primary aluminum (alpha) particle size is controlled in the process by limiting the slurry creation process to temperatures above the point at which solid alpha begins to form and alpha coarsening begins.

[0009] It is known that the dendritic structure of the primary solid of a semi-solid alloy can be modified to become nearly spherical by introducing the following perturbation in the liquid alloy near liquidus temperature or semi-solid alloy:

1) Stirring: mechanical stirring or electromagnetic stirring;
2) Agitation: low frequency vibration, high-frequency wave, electric shock, or electromagnetic wave;
3) Equiaxed Nucleation: rapid under-cooling, grain refiner;
4) Oswald Ripening and Coarsening: holding alloy in semi-solid temperature for a long time.

[0010] While the methods in (2)-(4) have been proven effective in modifying the microstructure of semi-solid alloy, they have the common limitation of not being efficient in the processing of a high volume of alloy with a short preparation time due to the following characteristics or requirements of semi-solid metals:

- High dampening effect in vibration.
- Small penetration depth for electromagnetic waves.
- High latent heat against rapid under-cooling.
- Additional cost and recycling problem to add grain refiners.
- Natural ripening takes a long time, precluding a short cycle time.

[0011] Temperature control has been found to be one of the most critical parameters for reliable and efficient semisolid processing *with a* comparatively short cycle time. As the apparent viscosity of semi-solid metal increases exponentially with the solid fraction, a small temperature difference in the alloy with 40% or higher solid fraction results in significant changes in its fluidity. In fact, the greatest barrier in using methods (2)-(4), as listed above, to produce semi-solid metal is the lack of stirring. Without stirring, it is very difficult and likely impossible to make alloy slurry with the required uniform temperature and microstructure, especially when there is a requirement for a high volume of the alloy. Without stirring, the only way to heat/cool semi-solid metal without creating a large temperature difference is to use a slow heating/cooling process. Such a process often requires that multiple billets of feedstock be processed simultaneously under a pre-programmed furnace and conveyor system, which is expensive, hard to maintain, and difficult to control.

[0012] While using high-speed mechanical stirring within an annular thin gap can generate high shear rate sufficient to break up the dendrites in a semi-solid metal mixture, the thin gap becomes a limit to the process's volumetric throughput. The combination of high temperature, high corrosion (e.g. of molten aluminum alloy) and high wearing of semi-solid slurry also makes it very difficult to design, to select the proper materials and to maintain the stirring mechanism.

One of the ways to overcome the above challenges is to apply electromagnetic stirring of the liquid metal when it is solidified into semi-solid ranges. Such stirring enhances the heat transfer between the liquid metal and its container to control the metal temperature and cooling rate, and generates the high shear rate inside of the liquid metal to modify the microstructure with discrete degenerate dendrites. It increases the uniformity of metal temperature and microstructure by means of the molten metal mixture. With a careful design of the stirring mechanism and method, the stirring drives and controls a large volume and size of semi-solid slurry, depending on the application requirements. The stirring helps to shorten the cycle time by controlling the cooling rate, and this is applicable to all type of alloys, i.e., casting alloys, wrought alloys, MMC, etc.

[0013] Vigorous electromagnetic stirring is the most widely used industrial process that permits the producation of a large volume of slurry. Importantly, this is applicable to any high-temperature alloys. Two main variants of vigorous electromagnetic stirring exist, one is termed "rotary" stator stirring due to the rotary flow pattern of the alloy within the vessel. The other is termed "linear" stator stirring due to the up and down flow loop of the alloy within the vessel.

[0014] With rotational or rotary stator stirring, the molten metal is moving in a quasi-isothermal plane, therefore, the degeneration of dendrites is achieved by dominant mechanical shear. US-A-4,434,837 describes an electromagnetic stirring apparatus for the continuous making of thixotropic metal slurries in which a stator having a single two pole arrangement generates a non-zero rotating magnetic field which moves transversely of a longitudinal axis. The moving magnetic field provides a magnetic stirring force directed tangentially to the metal container, which produces a shear rate of at least 50 /sec to break down the dendrites. With linear stator stirring, the slurries within the mesh zone are re-circulated to the higher temperature zone and remelted, therefore, the thermal processes play a more important role in breaking down the dendrites. US-A-5,219,018 describes a method of producing thixotropic metallic products by continuous casting with polyphase current electromagnetic agitation. This method achieves the conversion of the dendrites into nodules by causing a refusion of the surface of these dendrites by a continuous transfer of the cold zone where they form towards a hotter zone.

[0015] Further, an enabling disclosure regarding SOD technology can be obtained from U.S. Patents 6,399,017; 6,402,367; 6,432,160; 6,443,216; 6,611,736; 6,637,927; 6,742,567; 6,796,362; 6,845,809; 6,932,938; 6,991,670; 7,024,342; 7,132,077; 7.169,350.

[0016] As disclosed in the prior art forming the starting point of the invention (WO-A-01/91945) and as similarly disclosed in all other references cited the slurry-on-demand casting method is used with solid-fraction-ratios of 40% or higher. It has been accepted that with this only a restricted array of die cast alloys can be used.

[0017] The object of the present invention is to enable application of above explained SOD casting method to a wider area of die cast alloys and die casting applications.

[0018] The above noted object is met, according to the characterizing part of claim 1, by using the SOD casting method with a low-solid-fraction alloy, namely a 10 to 30% solid-fraction alloy. Preferably improvements of this invention are described in the dependent method-claims 2 to 6.

[0019] Further, above mentioned object is met with a SOD casting alloy charge that has a 10 to 30 % by weight solid-fraction. Here modifications and improvements are the subject matter of the dependent claims 8 to 11.

[0020] It has been found that the use of a 10 to 30 % solid-fraction enables usage of a wider array of die cast alloys, including alloys 380, 383, 360, and Mercalloy (commercially produced under such Trademark by Mercury Marine Division, Brunswick Corporation).

Hereafter follows a short description of the drawings. In the drawings

- Fig. 1 is a schematic sectional view illustrating a slurry apparatus for implementing the SOD casting method in accordance with the invention.
- Fig. 2 shows the vessel of Fig. 1.
- Fig. 3 is a top view of the vessel of Fig. 2.

[0021] Referring to Fig. 1 and the above noted prior art patents, vessel 10 contains a semi-solid casting alloy

12 and is carried on a fixture 14 on a transfer device such as robotic arm 16. The alloy is heated, e.g. in a furnace as in the above prior art patents, to a molten liquid state, and then poured or discharged into vessel 10, which is surrounded by an optional cooling sleeve or jacket 18, and may be separated therefrom by air gaps such as 20 for controlled cooling. Jacket 18 is disposed within an electromagnetic stirring device 22, e.g. a stator, supported by base plate 24 which may or may not be cooled. For the electromagnetic stirring means specific reference is made to initially mentioned WO-A-01/91945 and further to EP-A-1 563 929.

[0022] After cooling and magnetic stirring, the alloy is transferred while in a partial solid/liquid phase to a casting machine, all as is known and disclosed in the above noted and prior art patents. The noted transfer may be facilitated by a pouring spout 26 formed in the upper collar or lip of vessel 10, Figs. 2, 3.

[0023] In the present methodology, a SOD (slurry-on-demand) casting method casts a low-solid-fraction, namely 10 to 30% by weight solid-fraction alloy. This is in contrast to prior solid-fraction ratios of 40 to 60%. By way of analogy, the noted prior 40 to 60% solid-fraction ratio provides an ice cream-like or jello-like billet, whereas a 10 to 30% solid-fraction ratio provides a soupy milkshake-like or oatmeal-like charge or billet. It is has been found that the latter ratio, namely a low-solid-fraction, namely 10 to 30% solid-fraction, enables usage of a wider array of die cast alloys, including alloys 380, 383, 360, and Mercalloy (commercially produced under such Trademark by Mercury Marine Division, Brunswick Corporation).

[0024] The present method provides a slurry-on-demand casting method for casting a low-solid-fraction, namely 10 to 30% solid-fraction, alloy, including the steps of heating the alloy to a molten liquid state, e.g. in vessel 10 as above, cooling and stirring the alloy to nucleate and create a partial solid phase of the noted low-solid-fraction, and transferring the alloy while in the partial solid phase of the noted low-solid-fraction to a casting machine, as in the above noted prior art patents.

[0025] In the preferred embodiment of the present method, the alloy includes a pair of constituents of different melting point including a first constituent of a first melting point, and a second constituent of a second lower melting point. During the noted cooling and stirring step, the preferred embodiment of the present method cools the alloy below the first melting point but above the second melting point, whereafter the noted transferring step is performed. The first and second melting points are preferably selected close enough to each other such that during the cooling and stirring step, the solidification of the first constituent is limited to the noted low-solid-fraction until the second constituent begins to solidify, and then the transferring step is performed when the temperature of the alloy is between the noted first and second melting points.

[0026] In one preferred embodiment, the alloy is provided with aluminum as the first constituent and silicon as the second constituent. In this embodiment, it is preferred that the silicon content in the molten state increases from 9% to 12% $\pm$1% (in one preferred embodiment the latter being 12.6%) during the noted cooling step between the first and second melting temperatures whereby the amount of aluminum transitioning in phase from liquid to solid state is limited to the noted low-solid-fraction, wherein the eutectic composition of the alloy is at the noted 12.6% silicon.

[0027] Further, in the preferred embodiment, the noted first constituent is nucleated and solidified by magnetic stirring, as in the above noted prior art patents, without introducing a foreign object into the molten alloy. This is in contrast to prior art systems incorporating a rotating cooled rod, e.g. a graphite rod, introduced into a crucible of alloy to initiate the nucleation of solid phase particles.

[0028] Further, in the preferred embodiment, after the noted heating step, the alloy is transferred while in the molten liquid state to vessel 10, and then the cooling and magnetic stirring step is performed while the alloy is in vessel 10, and then the alloy is transferred in the noted partial solid phase of the noted low-solid-fraction from the vessel to the casting machine.

[0029] In the foregoing description, certain terms have been used for brevity, clearness, and understanding. No unnecessary limitations are to be implied therefrom beyond the requirement of the prior art because such terms are used for descriptive purposes and are intended to be broadly construed. The different configurations, systems, and method steps described herein may be used alone or in combination with other configurations, systems and method steps.

Claims

1. A SOD (slurry-on-demand) casting method for casting a solid-fraction alloy, comprising heating said alloy to a molten liquid state, cooling and stirring said alloy to nucleate and create a partial solid phase of said solid-fraction, and transferring said alloy while in said partial solid phase of said solid-fraction to a casting machine,
characterized in that
the method is used with a low-solid-fraction, namely 10 to 30% low-solid-fraction, alloy.

2. The method according to claim 1, **characterized in that**
said alloy comprises a pair of constituents of different melting points comprising a first constituent of a first melting point, and a second constituent of a second lower melting point, and comprising, during said cooling and stirring step, cooling said alloy below said first melting point but above said second melting point, and then performing said transferring step.

3. The method according to claim 2, **characterized in that**
it additionally comprises selecting said first and second melting points close enough to each other such that during said cooling and stirring step the solidification of said first constituent is limited to said low-solid-fraction until said second constituent begins to solidify, and performing said transferring step when the temperature of said alloy is between said first and second melting points.

4. The method according to claim 3, **characterized in that**
said alloy comprises aluminum as said first constituent and silicon as said second constituent,
wherein, preferably, the silicon content in said molten state increases from 9% to 12% ± 1% during said cooling step between said first and second melting temperatures whereby the amount of aluminum is limited to said low-solid-fraction.

5. The method according to claim 4, **characterized in that**
the eutectic composition of said alloy is at 12.6% silicon.

6. The method according to any one of the claims 2 to 5, **characterized in that** it additionally comprises nucleating and solidifying said first constituent by magnetic stirring and without introducing a foreign object into the molten alloy, wherein, preferably, the method further comprises, after said heating step, transferring said alloy while in said molten liquid state to a vessel, and performing said cooling and magnetic stirring step while said alloy is in said vessel, and then transferring said alloy in said partial solid phase of said low-solid-fraction from said vessel to said casting machine.

7. A SOD (slurry-on-demand) casting alloy charge, **characterized in that** it has a low-solid-fraction, namely 10 to 30% by weight solid-fraction.

8. The SOD casting alloy charge according to claim 7, **characterized in that** said 10 to 30% solid-fraction ratio provides a soupy milkshake-like charge, in contrast to an ice cream-like billet provided by a 40 to 60% solid-fraction ratio.

9. The SOD casting alloy charge according to claim 8, **characterized in that** said alloy comprises a pair of constituents of different melting points comprising a first constituent of a first melting point, and a second constituent of a second lower melting point,
wherein, preferably, said first and second melting points are close enough to each other such that during said cooling, the solidification of said first constituent is limited to said low-solid-fraction until said second constituent begins to solidify.

10. The SOD casting alloy charge according to claim 9, **characterized in that** said alloy comprises aluminum as said first constituent and silicon as said second constituent, in a composition so that the silicon content in a molten state increases from 9% to 12% ±1% during cooling between said first and second melting temperatures, such that the amount of aluminum is limited to said low-solid-fraction,
wherein, preferably, eutectic composition of said alloy is at 12.6% silicon.

11. The SOD casting alloy charge according to any one of the claims 8 to 10, **characterized in that**
said 10 to 30% solid-fraction alloy is a die cast alloy selected from the group consisting of alloys 380, 383, 360, and Mercalloy.

FIG. 1

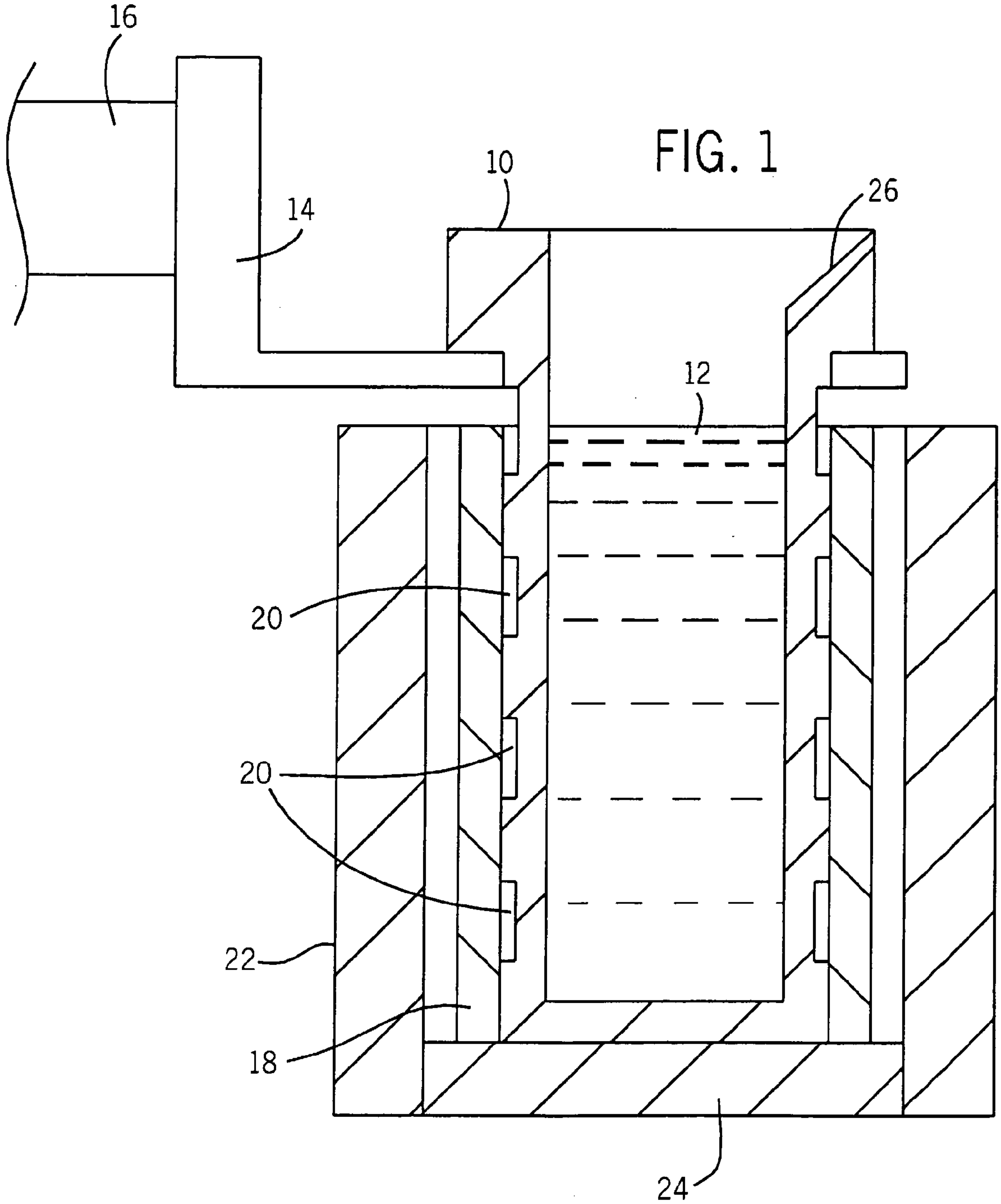


FIG. 2

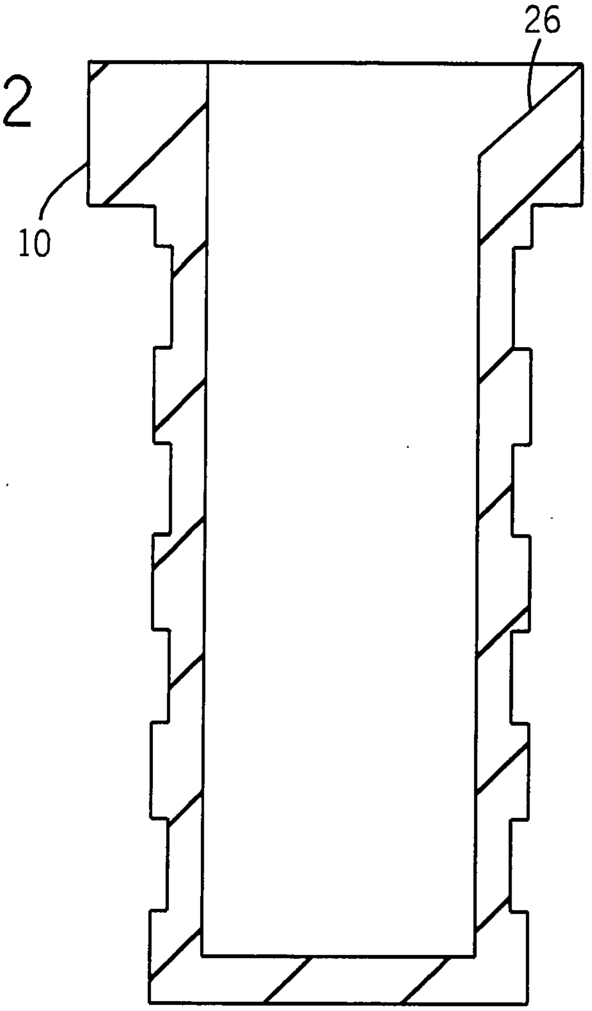
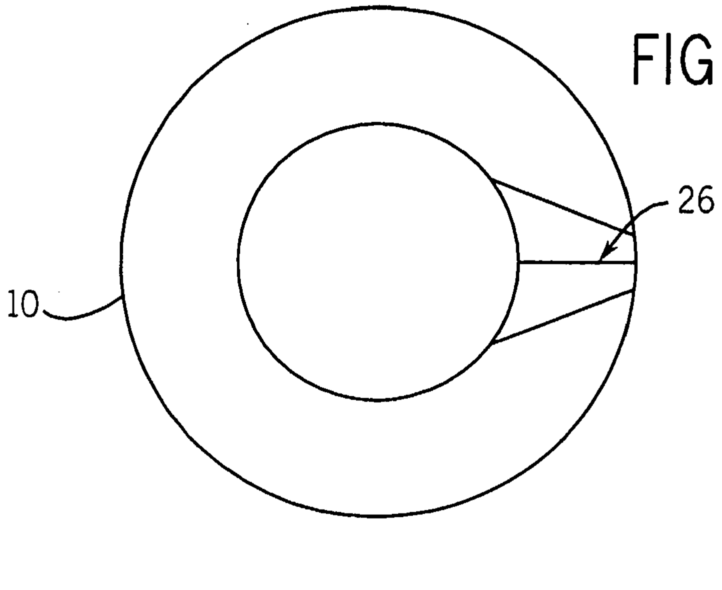


FIG. 3



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EUROPEAN SEARCH REPORT

Application Number
EP 07 01 3338

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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X	* examples 1,2 *	6	

TECHNICAL FIELDS SEARCHED (IPC)
B22D
C22C

The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
The Hague	19 December 2007	Scheid, Michael

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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