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(54) **Title:** VARIABLE-DENSITY COMPOSITE ARTICLES, PREFORMS AND METHODS

(57) **Abstract:** A metal matrix composite article that includes at least first and second regions, first and second reinforcement materials, a metal matrix composite material occupying the second region of the body and comprising a metal matrix material and the second reinforcement component, a preform positioned in the first region of the body and infiltrated by at least the metal matrix material of the metal matrix composite material. The article further includes a transition region located proximate an outer surface of the preform that includes a distribution of the second reinforcement component comprising a density increasing according to a second gradient in a direction toward the outer surface of the preform.



VARIABLE-DENSITY COMPOSITE ARTICLES, PREFORMS AND METHODS

CROSS-REFERENCES

[0001] This application claims the benefit of U.S. Provisional Application No. 61/802,277, filed March 15, 2013, the content of which is hereby incorporated by reference in its entirety.

FIELD

[0002] This disclosure relates generally to composites and castings having varying degrees of reinforcement, and relates more particularly to casting preforms, casted articles containing such preforms infiltrated with a matrix material, and to methods for making the same.

BACKGROUND

[0003] Traditional materials (e.g., metals, plastics, ceramics, resins, concrete, etc.) do not always provide components with all the requisite properties sufficient for adequate performance under field service conditions. As is well known, one manner of modifying and/or enhancing the final properties of a component is to reinforce the primary material making up the component with one or more additional materials. One class of reinforced materials are matrix composites, which are generally formed from traditional materials (e.g., a matrix material) that include one or more discrete reinforcement constituents (e.g., a reinforcement material or component) distributed within a continuous phase of the matrix material. Such matrix composites exhibit functional and structural characteristics that depend upon, for example, the properties of the reinforcement constituent(s), the architectural shape and geometry of such constituent(s), and the properties of the interfaces between and among different constituents and the matrix material.

[0004] Composite materials typically include one or more different types of reinforcement materials. Particle reinforcement often includes non-metallic, and commonly ceramic, particles (e.g., SiC, Al₂O₃, etc.), but may include a variety of particles and materials that provide advantages or reinforcement for one or more properties of the matrix composite. Reinforcement of matrix material with fibers, including continuous-fibers, monofilament, and/or short-fibers is also known in the art. Generally, different types of matrix composites require or are typically associated with different primary processing routes/methods. Examples of different processes for forming matrix composites include, though are not

limited to, in-situ reactive processes, diffusion bonding, blending and consolidation, vapor deposition and consolidation, liquid-state processing, stir casting/slurry casting, centrifugal casting, and infiltration processes involving infiltration of matrix material into porous preforms.

[0005] Some existing manufacturing and forming processes are designed to provide distributions of a reinforcement material within a matrix material. In some cases the reinforcement material may be distributed uniformly throughout an area, while in other cases the distribution may be non-uniform. In many cases, though, limitations with past techniques have led to less than desirable outcomes, resulting in a continuing search for forming processes, and corresponding composite materials, that exhibit desired structural and/or functional properties.

[0006] A brief overview of some processes that have been used to form composite materials will now be provided. *In situ* selective reinforcement methods involve placing and positioning a pre-cast reinforcement material member (sometimes referred to as a 'preform') into a near net-shape casting mold. Matrix material is then cast around the reinforcement member to form the composite. While the amount and/or density of pre-cast reinforcement material can be varied as desired, the constituent material of the reinforcement members does not become integrated (e.g., mixed or infiltrated) with the matrix material, except perhaps in a limited extent at the interfacial boundaries between the reinforcement member and the unreinforced matrix material. Therefore, such *in situ* methods are hindered by abrupt and problematic differential coefficients of thermal expansion ('CTE') between the matrix material and reinforcement member. Such abrupt transitions in CTE at the matrix-reinforcement interface boundaries can give rise to residual stress during the forming process (e.g., residual stress-concentration), and also manifest in stress fractures during thermal cycling of the reinforced components during service.

[0007] Another example of *in situ* selective reinforcement involves *infiltration casting* of matrix material into porous preforms positioned in near net-shape casting molds. The structure of the porous preform includes a reinforcement constituent, which may be uniform or non-uniform. One advantage of preform infiltration casting is that the method is relatively fast, thus resulting in a more integrated, infiltrated preform with substantially more contact area between the reinforcement and matrix materials. Even so, the materials still exhibit abrupt transitions in CTE at the interface/boundaries between the preform and the

unreinforced matrix material that can create the stress problems noted above. Additionally, there are practical limits to the amount and density of reinforcement material that can be placed within a porous preform, because resistance to infiltration casting substantially increases at high reinforcement levels (e.g., beyond 15% to 20% material in the preform). In addition, the thickness and cross-sectional area of such preforms must be limited to allow complete infiltration prior to cooling of the matrix material.

[0008] Centrifugal casting techniques have been used to selectively reinforce composite materials by favorably placing or distributing reinforcement material to form gradient or layered distributions of the reinforcement material within the matrix material. While abrupt transitions in the coefficient of thermal expansion ('CTE') at the matrix-reinforcement interface boundaries can be reduced in centrifugal embodiments where continuous particle gradients are formed within the matrix material, such methods still suffer from differential CTE effects in cost-effective embodiments comprising layered reinforcement particles. Additionally, in centrifugal methods, the attainable variations of particle distributions are limited to bands or layers and/or continuous gradients, and if different reinforcement particle types having differing densities are simultaneously used, it may be impossible to get adequate coordinate (co-localized) particle gradient distributions for the divergent particle types, or to get the different particle types where they are needed, and in the desired pattern.

[0009] In further examples, another type of selective reinforcement involves the deposition or spraying (e.g., by low or high velocity spray techniques) of reinforcement particles onto the surface of near net-shape matrix material castings. One drawback of such methods for these applications is that the spray or deposition is superficial, because it is applied to the surface of solid matrix material castings, and does not substantially penetrate beyond the surface. Additionally, such superficial reinforcement coatings must generally be significantly machined prior to placing the reinforced casting into service. Moreover, absent resurfacing with more reinforcement, the effective service life of such castings is over once the superficial reinforcement layer is worn and/or otherwise degraded. Furthermore, in such superficial reinforcement applications, bonding and integration of the sprayed/deposited reinforcement with the matrix material is limited, even with the most optimal spray/deposition methods.

[0010] Gelcasting methods are another way to make functional gradient materials having preforms. In gelcasting, gradient reinforced preforms can be formed using gravitational or

centrifugal forces to achieve a vertical composition gradient in molded slurries. The preforms may then be subsequently infiltrated. As with centrifugal casting embodiments, the attainable variations of particle distributions for preform gelcasting methods are limited to layers and/or continuous gradients. If different reinforcement particle types having differing densities are simultaneously desired/used, it may be impossible to get adequate coordinate (co-localized) particle gradient distributions for the divergent particle types, or to get the different particle types where they are needed, and in the desired pattern. Additionally, preforms made by such gelcasting methods are problematic because of excessive warpage and anisotropic shrinkage occurring during the sintering stage because of different sintering kinetics for the material components.

[0011] Accordingly, methods and processes exist to form composite materials, as well as composite materials having varying material densities such as reinforcement material gradients and other distributions, both non-uniform and uniform. As discussed above, though, limitations with past techniques have led to a continuing search for improved processes for forming composite materials, and corresponding composite materials and articles exhibiting improved and/or desired structural and/or functional properties.

SUMMARY

[0012] One embodiment includes a metal matrix composite article, comprising a cast, reinforced body. The body has a first region and a second region with the first region having more reinforcement than the second region. The article also includes a first reinforcement material, a second reinforcement material, a metal matrix composite material occupying the second region of the body and a preform positioned in the first region of the body. The metal matrix composite material comprises a metal matrix material and the second reinforcement component. The preform is infiltrated by at least the metal matrix material of the metal matrix composite material and further comprises a first end, a second end, an outer surface, the first reinforcement component, and a porous structure configured to allow passage of the metal matrix material into the preform and to block or reduce passage of the first reinforcement component into the preform. The first reinforcement component comprises a density increasing between the first end of the preform and the second end of the preform according to a first gradient. The article further includes a transition region of the body located proximate the outer surface of the preform that includes a distribution of the second reinforcement component adjacent to the outer surface of the preform, the distribution of the

second reinforcement component comprising a density increasing according to a second gradient in a direction toward the outer surface of the preform.

[0013] These and various other features and advantages will be apparent from a reading of the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The following drawings illustrate some particular embodiments of the present invention and therefore do not limit the scope of the invention. The drawings are not to scale (unless so stated) and are intended for use in conjunction with the explanations in the following detailed description. Some embodiments will hereinafter be described in conjunction with the appended drawings, wherein like numerals denote like elements.

[0015] FIG. 1 is a flow diagram illustrating an example of cavity and preform filling according to an embodiment of the invention.

[0016] FIG. 2 is a depiction of a functional reinforcement gradient according to an embodiment of the invention.

[0017] FIG. 3 is an enlarged portion of the functional reinforcement gradient of FIG. 2 according to an embodiment of the invention.

[0018] FIGS. 4A-4C are enlarged views of the functional reinforcement gradient of FIG. 2 according to an embodiment of the invention.

[0019] FIG. 5 is a perspective view of a brake assembly according to an embodiment.

[0020] Fig. 6 is a sectional view of a brake rotor according to an embodiment.

[0021] Fig. 7 is a sectional view of a brake rotor according to an embodiment.

[0022] FIGS. 8A-8E illustrate a method of making a metal matrix composite brake rotor according to an embodiment.

[0023] FIG 9. illustrates a method of making a metal matrix composite brake drum according to an embodiment.

[0024] FIG. 10 illustrates a view a close up views of a functional reinforcement gradient formed by a method of depositing a preform slurry according to an embodiment.

[0025] FIGS. 11A-11D illustrate a method for making a variable-density preform according to an embodiment.

[0026] FIG. 12 illustrates a method for making a variable-density preform according to an embodiment.

[0027] FIGS. 13 and 14 illustrate working surfaces for making a variable-density preform according to embodiments.

DETAILED DESCRIPTION

[0028] The following detailed description is exemplary in nature and is not intended to limit the scope, applicability, or configuration of the invention in any way. Rather, the following description provides some practical illustrations for implementing some embodiments of the present invention. Examples of constructions, materials, dimensions, and manufacturing processes are provided for selected elements, and all other elements employ that which is known to those of ordinary skill in the field of the invention. Those skilled in the art will recognize that many of the noted examples have a variety of suitable alternatives.

[0029] Certain embodiments described in this disclosure provide and/or relate to an automotive brake rotor having a lightweight Metal Matrix Composition (MMC) which provides the ability to tailor the structure and the properties to meet certain variable and severe thermal and mechanical loadings. In addition to the thermal and mechanical attributes, the MMC technology provides a cost effective method for manufacturing brake rotors.

[0030] According to some embodiments, one or more preforms can be manufactured with one or more Functional Reinforcement Gradients (FRG) as disclosed in Applicant's co-owned U.S. Patent No. 8,075,827 B2, titled "Variable-Density Preforms" issued December 13, 2011, and in Applicant's co-owned and co-pending U.S. Patent Application No. 13/323,118, titled "Variable-Density Preforms" filed December 13, 2011 (now U.S. Patent Application Publication No. 2012/0227624 A1, dated September 13, 2012). Each of these patents and publications is hereby incorporated herein in their entirety by reference.

[0031] Briefly, in accordance with an embodiment of the invention, one or more FRG in a preform is formed by establishing a flow of ceramic slurry into a mold and then filtering the slurry so as to extract and remove the liquid, thereby creating (or leaving behind) a functional gradient of the ceramic media contained in the slurry. In some embodiments, such processes can yield an FRG of approximately 30% to 45% by volume on the friction surface.

[0032] The instant application discloses embodiments wherein the volume fraction can range from this high reinforcement level found on the frictional surface to a very low or approximately 0% reinforcement level required in other areas. The disclosed embodiments are well suited for, but not limited to, automotive and airplane applications, including rotor brake systems for heavy trucks and/or trailers. Embodiments disclosed herein provide one or more advantages or features over past practices. For example, two-piece rotors have been used in industry (e.g., Brembo, Performance Friction) to date because it is extremely difficult to maintain rotor flatness during a transient braking event. The instant application discloses embodiments that overcome this and/or other deficiencies. In one example, the use of a functional reinforced gradient can assist in overcoming these types of problems.

[0033] As is generally known in the art, when a brake is used for slowing and/or stopping a moving object, the motion of the object gets transformed into heat and transferred to the brake disc in order to stop the moving vehicle. Upon application of the brake actuator the disk is clamped between the brake pads and rotational drag is created. This clamping causes energy transformation to take place and heat is generated. Under certain operating conditions, the heat energy does not get transferred to the disk uniformly over the whole surface due to the differences in tangential (or linear) velocities along the radius of the brake pad interface. The tangential speed of the brake rotor at any radial distance, r , from the rotor center is defined as the product of $2\pi r$ and the rotational speed (i.e., $((2\pi r) \times (\text{RPM}))$). As will be apparent, a higher velocity found at the outer positions corresponds to a higher thermal energy state (i.e. higher temperatures). Therefore, the rotor thermal load carrying abilities at the outer locations needs to handle the higher heat energy generated there.

[0034] In accordance with an embodiment, higher heat capacity/handling can be accomplished through placement of a higher concentration of ultra-high temperature ceramic material at specific locations on the rotor. In some embodiments, the coefficient of thermal expansion (CTE) is tailored with the changing of the ceramic component in the MMC content such that the rotor will expand and contract while remaining in-plane. Control of expansion

and contraction is not possible if a monolithic material such as cast iron is used in a brake rotor. This is one of the reasons why 'brake jitter' is noticed in a monolithic cast iron automotive braking system.

[0035] Accordingly, some embodiments disclosed herein provide the ability to control the expansion and contraction of the rotor during braking (e.g., due to heating and cooling), enabling embodiments of the rotor(s) of the invention disclosed in the instant disclosure to be 'hard mounted' to the hub. While other material options may contain better material properties in terms of maximum operation temperatures, the ability to tailor (or customize) the FRG material properties as taught herein allows for effective mounting of the friction surfaces directly to the hub section of the rotor and more effective thermal management to avoid brake fade (i.e., reduced braking action).

Exemplary Embodiments

[0036] In accordance with some embodiments of the invention, the volume fraction of ceramic in the brake rotor changes across the braking surface extending between the inside and the outside diameters of the rotor. For instance, in a non-limiting exemplary embodiment, a location or section proximate the outermost extent (for example proximate the circumference) of the brake disc can include approximately 40% to 45% by volume of ceramic reinforcement and approximately 55% to 60% by volume of one or more light alloy; whereas at some location other than the outermost extent, e.g., proximate the hub or at a section or location between the hub and the circumference, the brake disc can include approximately 30% to 35% by volume of ceramic reinforcement and approximately 65% to 70% by volume of one or more light alloy. A method for making such changes in volume fraction is taught by Applicant's granted patent, U.S. Pat. No. 8,075,827 B2, titled "Variable-Density Preforms" issued December 13, 2011.

[0037] In some cases distinct zones and interfaces between zones are provided. For example, certain embodiments of brake rotors include at least three functional zones, viz., a) friction interface (heating zone), b) venting (cooling zone) and c) mounting hub (torque transfer zone). In some cases these zones should or must have specific material attributes for the rotor, as a whole, to function properly. They also must have the proper interfaces between the zones. High ceramic on the rotor's braking surface, for example proximate the outermost extent, must be graded to a lower ceramic content in the radial direction extending

between the circumference and the hub, and through the thickness toward the internal venting.

[0038] In some cases an exemplary design according to some embodiments involves the use of two preforms to cast an article such as a blade or brake rotor. In some cases the two preforms are functionally graded in the radial direction. In some embodiments, the blades are infiltrated during the casting process that creates all of the rotor geometry such as, but not limited to, the hub, venting, and blade section, etc.

[0039] In certain embodiments, the effluent (or slurry) can be, but is not limited to, an aluminum or magnesium alloy containing ceramic particles and/or fibers.

[0040] In some embodiments, the at least one exit end or orifice can be, but is not limited to, a functionally graded porous preform.

[0041] In certain embodiments, a secondary gradient can be developed at the metal-preform interface of a casted article.

[0042] In some embodiments, the functional gradient in the interface regions can serve, but is not limited to, one or more of the following: (1) to provide a continually changing ceramic structure so as to minimize the stress riser at the interface from the mechanical loading; and/or (2) to grade the differences in the CTE at the interface to reduce the thermal stresses developed at the interface. In a braking event, the thermal load is just as important if not more important than that of the mechanical load.

[0043] In some embodiments of the invention, the thickness of the FRG can be altered by changing one or more of the density or the thickness or the composition of the preform in the die cavity. In certain embodiments, the preform and the incoming ceramic carrying aluminum can be tailored such that a predetermined FRG is achieved at the one or more interfaces. In some embodiments, the fraction of the fiber and/or particle combination can be altered to increase or decrease the thickness of the transition region.

[0044] Accordingly, in some embodiments, the preform can contain ceramic particles or continuous ceramic fibers or discontinuous ceramic fibers or any combination thereof in an amount ranging between approximately 5% to approximately 70% by volume. In certain embodiments, the incoming alloy or slurry can include ceramic particles and/or ceramic

fibers in an amount ranging between approximately 5% to 40% by volume. In some embodiments, vibration can be induced during the molding process to initiate and/or enhance the dispersion of the ceramic for providing a predetermined gradient.

[0045] As is well known in the art, different materials have different coefficients of thermal expansion (CTE) and therefore each expands at a different rate when heated. Accordingly, if different material having different CTE are attached to one another, the thermal stress at the interface and in the vicinity thereof can be substantially, and in some cases significantly, high when heated. Accordingly, providing or creating an FRG can reduce, minimize, and/or eliminate such thermal stresses as may arise due to the differences (or mismatch) in the CTE of the material used in the rotor.

[0046] Thermal stress in a constrained material is defined by $\sigma = \alpha E \Delta T$ where σ is thermal stress, α is the material's coefficient of thermal expansion (CTE), E is the material's Young's modulus and ΔT is the change in temperature. The CTE (α) of unreinforced aluminum is approximately 22.9 $\mu\text{m}/\text{m}^\circ\text{C}$ (in the temperature range of approximately 20°C to approximately 300°C); whereas for a 40% SiC particulate reinforced aluminum, the CTE (α) is approximately 11 $\mu\text{m}/\text{m}^\circ\text{C}$. Accordingly, at approximately 300°C, the stress in the aluminum and at the interface between the aluminum and the MMC, respectively, would be

$$\begin{aligned}\sigma_{\text{Al-MMC}} &= ((22.9 - 11 \mu\text{m}/\text{m} - ^\circ\text{C}) * 124\text{E}9 \text{ N}/\text{m}^2 * 300^\circ\text{C}) = 443.39 \text{ MPa} \\ (64.26\text{ksi})\sigma_{\text{Al}} &= ((22.9 - 11 \mu\text{m}/\text{m} - ^\circ\text{C}) * 69\text{E}9 \text{ N}/\text{m}^2 * 300^\circ\text{C}) = 246.33 \text{ MPa (36ksi)}\end{aligned}$$

[0047] This indicates that failure would occur in the MMC as the stress in each material is at the yield point of many alloys at room temperature and exceeds the yield of almost all reinforced and unreinforced aluminum alloys at 300°C. This is why a functional gradient can be desirable at this interface in some cases. If an incremental change in volume fraction is implemented, the thermal stress can be effectively managed.

[0048] Taking the same temperature change as above but with an incremental CTE difference (directly related to volume fraction of ceramic in the MMC by rule of mixtures), the stress at the interface is computed as:

$$\begin{aligned}\sigma_{\text{Al}} &= ((22.9 - 20 \mu\text{m}/\text{m} - ^\circ\text{C}) * 69\text{E}9 \text{ N}/\text{m}^2 * 300^\circ\text{C}) = 60 \text{ MPa (8.7ksi)} \\ \sigma_{\text{Al-MMC}} &= ((22.9 - 20 \mu\text{m}/\text{m} - ^\circ\text{C}) * 124\text{E}9 \text{ N}/\text{m}^2 * 300^\circ\text{C}) = 108 \text{ MPa (15.7ksi)}\end{aligned}$$

[0049] The resultant thermal stress is more manageable in both materials and hence will be able to handle the repeated loadings it will experience during braking events.

[0050] Accordingly, in an embodiment having the interface modification in accordance with an embodiment of the invention, the high volume fraction reinforcement can be graded to a low or no reinforcement smoothly.

[0051] Machining attributes – SiC reinforced alloys are known to be very difficult to drill and tap. The ability of putting high levels of reinforcement only on the braking surface helps reduce machining time and cost. Historically, the rotors that have been in production in automotive applications have been fully reinforced all the way to the hub.

[0052] In some embodiments, the friction face may contain up to approximately 45% ceramic while the hub of the rotor is > approximately 5% ceramic.

[0053] Non-limiting exemplary products in which the embodiments of the invention disclosed herein can be implemented include, but is not limited to, one or more of those illustrated and described below:

[0054] Some products this technology covers include the following: Automotive, Military, Commercial Truck and trailer rotors – each friction face is reinforced with a preform based MMC and a functional gradient is added to between the preform areas and unreinforced areas.

[0055] An exemplary process in some embodiments means that the effluent passes through a porous media to build a functional gradient at the preform interface. In a non-limiting exemplary embodiment, the effluent in this case is a light alloy (aluminum, magnesium or silicon) that contains some percentage of ceramic media. For example Duralcan (10% SiC particulate). In accordance with an embodiment of the invention, the preform can be used as die wherein the effluent passes through but the particles are held back (or retained) so as to accumulate (or dam up).

[0056] With reference to the figure immediately below, a non-limiting exemplary embodiment includes approximately 90% aluminum and approximately 10% ceramic short fibers and/or particulate. Preform having an average of approximately 40% ceramic reinforcement and approximately 60% void.

[0057] In a non-limiting exemplary embodiment, the preform thickness for the friction surface of a rotor is set at approximately 0.234" thick (approximately 6mm) for a square inch, this is approximately 0.234 cubic inches of volume of which approximately 0.1404 cubic inches (approximately 60%) is void ($0.1404 \text{ cubic inches} = 0.60 * 0.234 \text{ cubic inches}$). The interface volume fraction will build to equal the preform volume fraction of approximately 40% and decrease linearly away from the interface as the alloy is pressed from the stir cast material into the preform. The volume fraction evens out at the original MMC stir cast volume fraction (i.e. approximately 10%). So the slope to determine transition zone thickness at the interface is determined by the volume of alloy lost to the preform and the velocity of the shot.

[0058] In accordance with an embodiment of the invention, a similar resultant FRG MMC structure can be obtained by a spray application of the preform. A non-limiting exemplary embodiment includes a process by which a high concentration of particles is used in a preform slurry and sprayed thru a nozzle (e.g., a venturi nozzle) onto a heated surface or plate on which vacuum is applied (to drive off the excess water/effluent). In some embodiments of the invention, the slurry composition can then be altered after the desired build up of ceramic structure to a higher fiber containing mix to create a less dense ceramic structure. In certain embodiments of the invention, such build up of an FRG can provide a structure similar to that previously described without the need to cast with a ceramic containing alloy. In accordance with an embodiment of the invention, the preform can be dried and fired, as previously described, to dry out moisture and/or burn out organic binders and/or sinter the inorganic binders to yield a preform ready for casting. In accordance with an embodiment of the invention, the structure can then be cast using a pressure infiltration method (e.g., squeeze casting). The figure below illustrates a non-limiting exemplary embodiment of a structure within a casting manufactured in accordance with an embodiment of the invention.

[0059] In some embodiments, the preform mix progresses from all fibers to a combination of low fibers and high particles to all particles. The light area, in an embodiment of the invention, is the alloy that has infiltrated the mix.

[0060] In some embodiments, the preform mix progresses from all fibers to a combination of high fibers and low particles to a combination of low fibers and high particles to all particles.

[0061] In certain embodiments, the disclosed spraying process of the instant invention could be used to spray an existing preform (e.g., a preform having high volume of SiC particles) with a fiber-particle layer and then a fiber layer prior to squeeze casting so as to minimize stress concentrations that may arise due to differences in, and not limited to, the CTE and stiffness at one or more interfaces of mating materials.

[0062] In some cases a process by which a high concentration of particles is used in a preform slurry and sprayed or deposited thru a venturi nozzle or otherwise deposited onto a heated or unheated surface or plate on which vacuum and/or a centrifugal force is applied (to drive off the excess water/effluent). The slurry composition can then be altered after the desired build up of ceramic structure to a higher or lower fiber ceramic containing density mix to create a less/or more more or less dense ceramic structure. This build up of an FRG obtains a similar structure to that above without the need to cast with a ceramic containing alloy. This preform is dried and fired in the same common practice as before spelled out in authors' patent, but the drying process may also be used in between compositional layer changes as well.. To This drying process driesy the final moisture out, burns out the organic binders and to sinters the inorganic binders to obtain a preform ready for casting.

[0063] This structure can then be cast using a pressure infiltration method (i.e. squeeze casting). The final structure of the casting is seen below. The preform mix moves from all fiber to low fiber-high particle to all particle mix. The light area is the alloy that has infiltrated the mix.

[0064] Thus, embodiments of the invention are disclosed. Although the present invention has been described in considerable detail with reference to certain disclosed embodiments, the disclosed embodiments are presented for purposes of illustration and not limitation and other embodiments of the invention are possible. One skilled in the art will appreciate that various changes, adaptations, and modifications may be made without departing from the spirit of the invention and the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A metal matrix composite article, comprising:
a cast, reinforced body, the body comprising a first region and a second region, the first region having more reinforcement than the second region;
a first reinforcement material;
a second reinforcement material;
a metal matrix composite material occupying the second region of the body and comprising a metal matrix material and the second reinforcement component;
a preform positioned in the first region of the body and infiltrated by at least the metal matrix material of the metal matrix composite material, the preform comprising
a first end,
a second end,
an outer surface,
the first reinforcement component, the first reinforcement component comprising a density increasing between the first end of the preform and the second end of the preform according to a first gradient, and
a porous structure configured to allow passage of the metal matrix material into the preform and to block or reduce passage of the first reinforcement component into the preform; and
a transition region of the body located proximate the outer surface of the preform, the transition region comprising a distribution of the second reinforcement component adjacent to the outer surface of the preform, the distribution of the second reinforcement component comprising a density increasing according to a second gradient in a direction toward the outer surface of the preform.
2. The metal matrix composite article of claim 1, wherein the metal matrix material comprises a metal or a metal alloy and wherein the second reinforcement component comprises a ceramic particle component and/or a ceramic fiber component.
3. The metal matrix composite article of claim 2, wherein the metal matrix material comprises aluminum, magnesium, or an alloy thereof.

4. The metal matrix composite article of claim 1, wherein the first reinforcement component comprises a ceramic particle component and/or a ceramic fiber component.
5. The metal matrix composite article of claim 1, wherein the transition region comprises a thickness corresponding to an amount of the metal matrix material infiltrated into the preform.
6. The metal matrix composite article of claim 1, wherein the distribution of the second reinforcement component at the outer surface of the preform comprises a first volume fraction that matches a volume fraction of the first reinforcement component at the outer surface of the preform.
7. The metal matrix composite article of claim 6, wherein the metal matrix composite material comprises the second reinforcement component at a minimum volume fraction, and wherein the volume fraction of the distribution of the second reinforcement component decreases linearly or substantially linearly from the first volume fraction to the minimum volume fraction.
8. The metal matrix composite article of claim 1, wherein the article is a cast brake rotor.
9. The metal matrix composite article of claim 8, wherein the first region comprises a friction face and the second region comprises a hub.
10. The metal matrix composite article of claim 8, further comprising a second preform positioned in the first region of the body adjacent to the first preform, the second preform infiltrated by at least the metal matrix material of the metal matrix composite material.
11. A method for making a metal matrix composite article, comprising:
providing a porous preform comprising a first end, a second end, an outer surface, and a first reinforcement component, the first reinforcement component comprising a density increasing between the first end of the preform and the second end of the preform according to a first gradient;
positioning the preform within a die cavity;

introducing a molten metal matrix composite material into the die cavity about the preform, the metal matrix composite material comprising a liquid component and a second reinforcement component;
pressurizing the molten metal matrix composite material, thereby
infiltrating the preform with at least the liquid component, and
forming a distribution of the second reinforcement component adjacent to the outer surface of the preform, the distribution of the second reinforcement component comprising a density increasing in a direction toward the outer surface of the preform according to a second gradient.

12. A method for making a variable-density preform, comprising:
providing a preform slurry comprising a liquid component, at least a first reinforcement component, and a first density;
depositing a first layer of the preform slurry at the first density onto a working surface;
changing the density of the preform slurry from the first density to a second density;
depositing a second layer of the preform slurry at the second density on top of the first layer of the preform slurry;
removing the liquid component from the preform slurry as it is deposited on the working surface; and
drying the layers of the preform slurry deposited on the working surface to remove residual amounts of the liquid component;
wherein the first and the second layers of the dried preform slurry comprise a reinforcement density gradient corresponding to the first density and the second density.

13. The method of claim 12, wherein changing the density of the preform slurry from the first density to the second density comprises adding at least a second reinforcement component to the preform slurry, wherein the second layer of the preform slurry comprises at least the first reinforcement component and the second reinforcement component.

14. The method of claim 13, further comprising changing the density of the preform slurry from the second density to a third density by removing the first reinforcement component from the preform slurry, and then depositing a third layer of the preform slurry at the third density on top of the second layer, the third layer comprising the second reinforcement component but not the first reinforcement component.

15. The method of claim 12, wherein depositing the layers of the preform slurry on the working surface comprises at least one of pouring the preform slurry on the work surface and spraying the preform slurry on the work surface.
16. The method of claim 12, wherein the working surface comprises a vacuum table for removing the liquid component from the preform slurry.
17. The method of claim 12, wherein the first reinforcement component is a reinforcement fiber component or a reinforcement particle component.
18. The method of claim 13, wherein the first reinforcement component comprises a reinforcement fiber component and the second reinforcement component comprises a reinforcement particle component.
19. The method of claim 12, further comprising pressing the first and the second layers of the preform slurry to a desired thickness
20. The method of claim 12, further comprising changing the density of the preform slurry from the second density to two or more additional densities, and then depositing corresponding layers on the working surface to build up the preform.

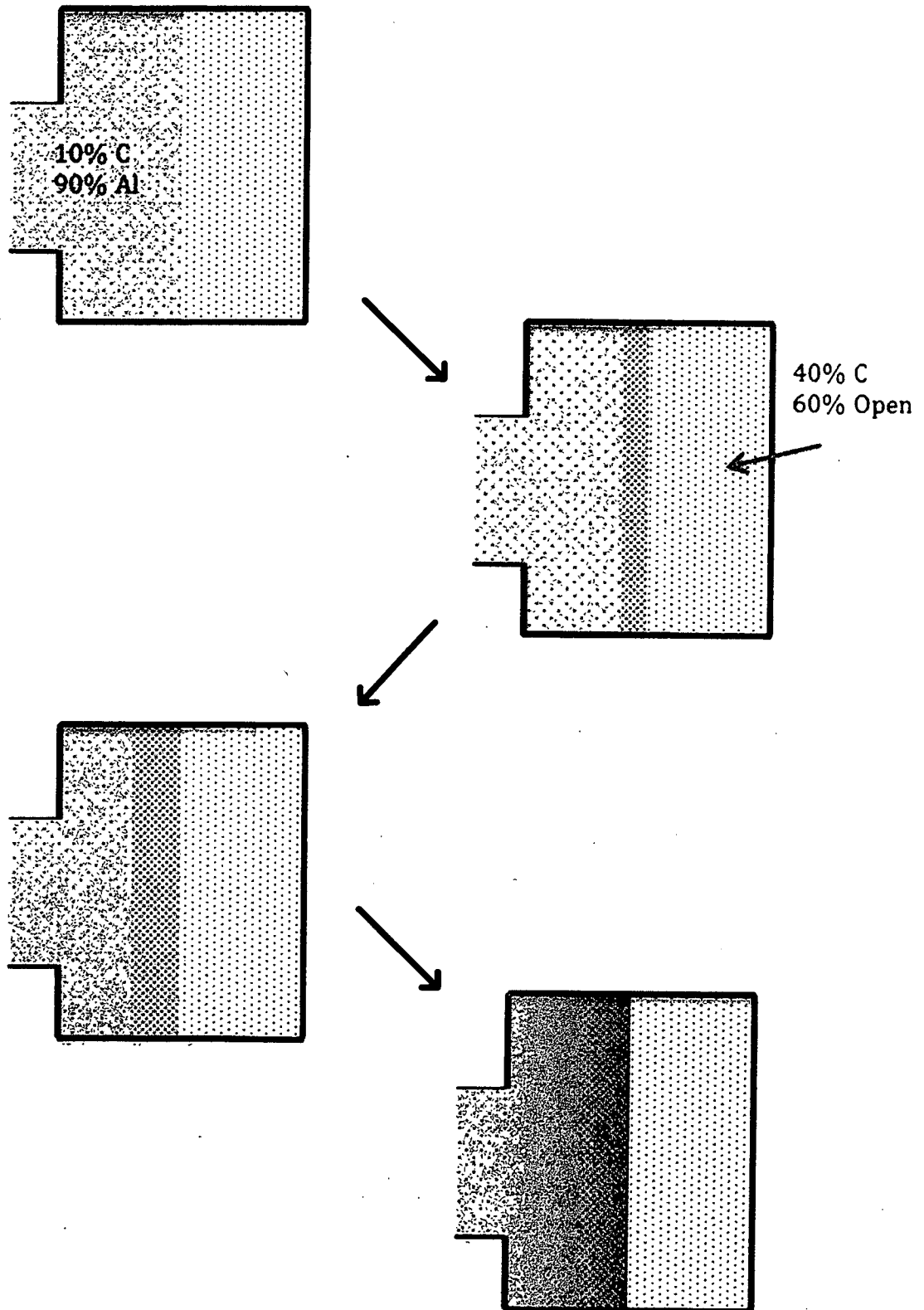


Fig. 1

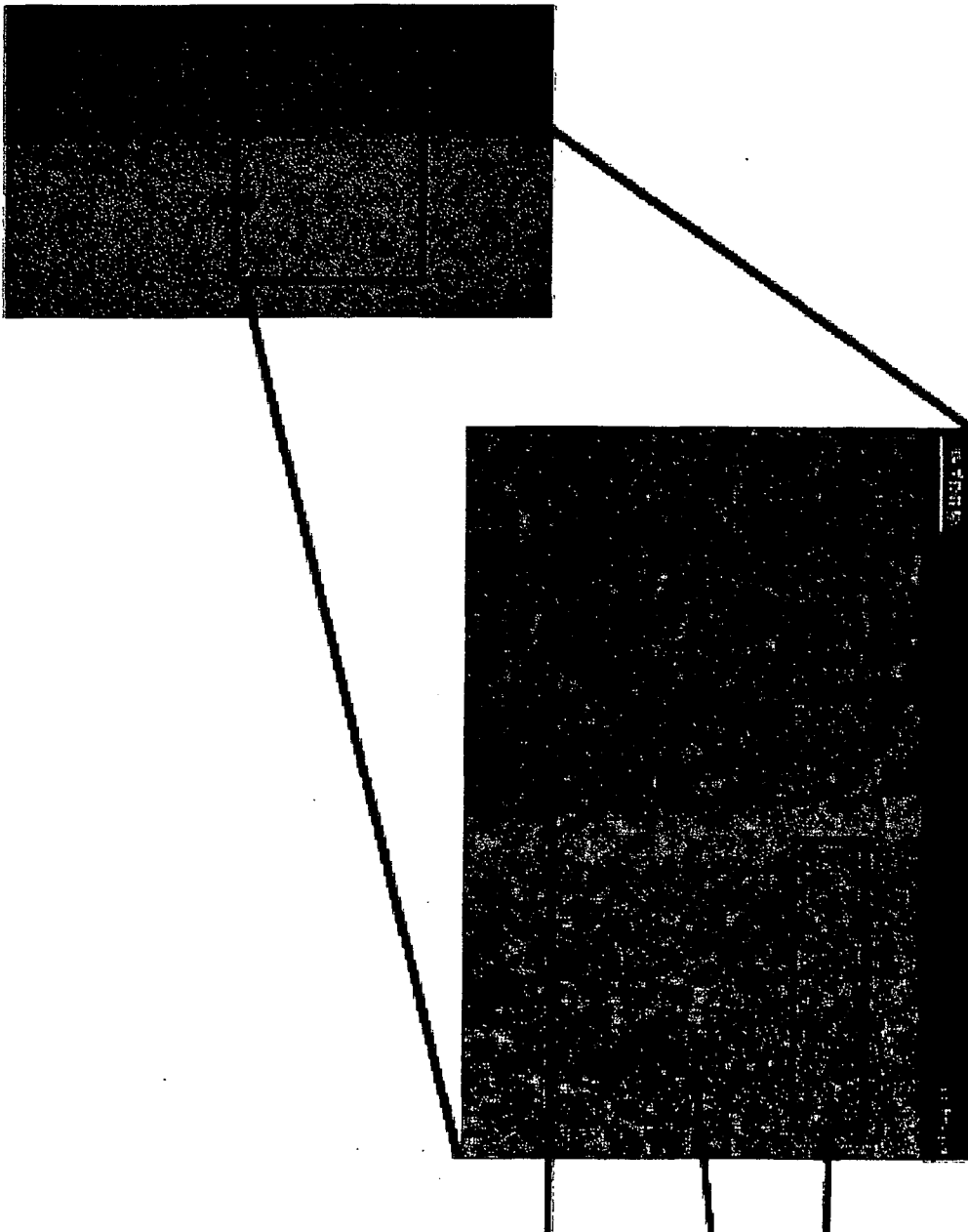


Fig. 2

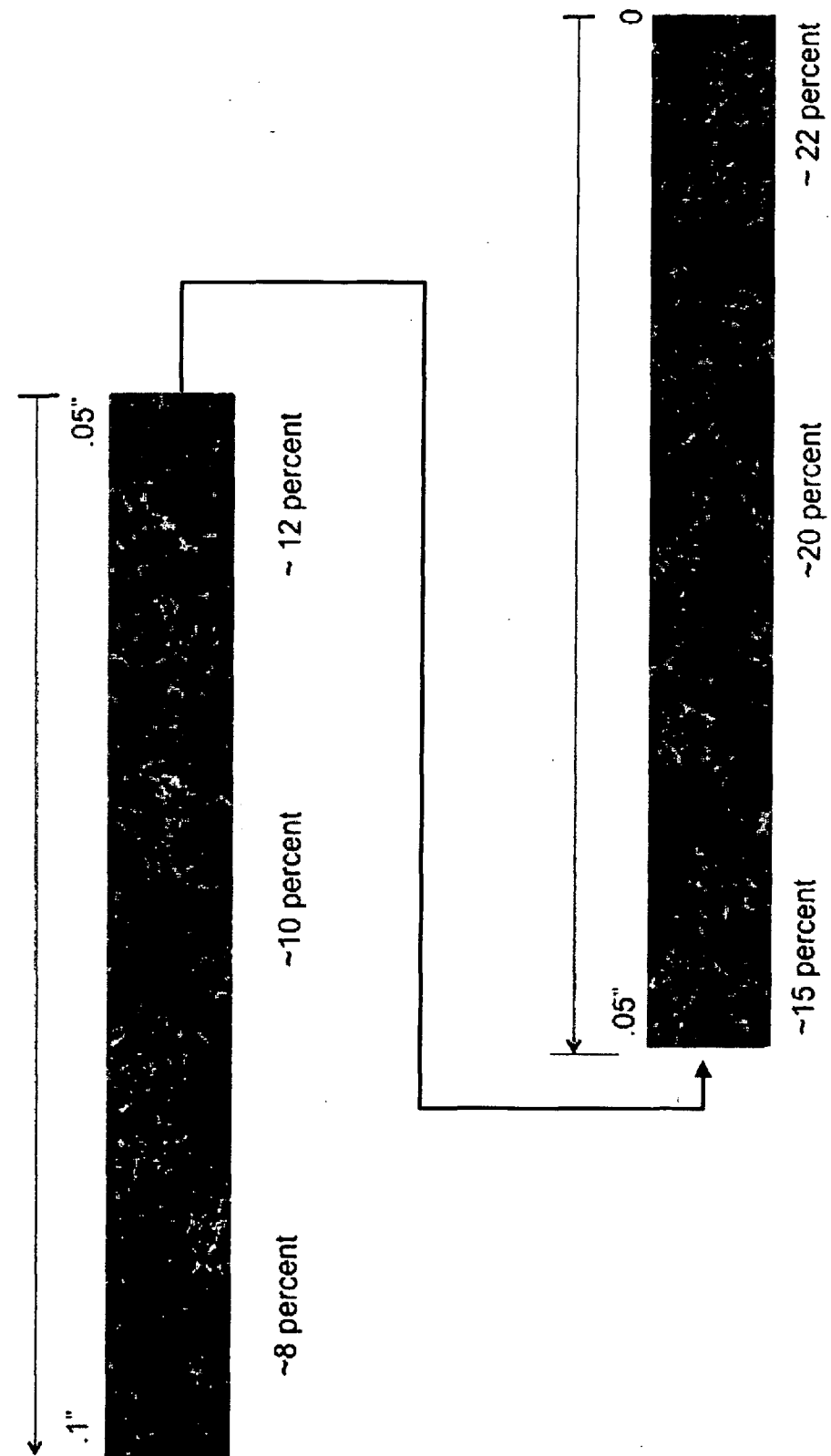


Fig. 3

Fig. 4A

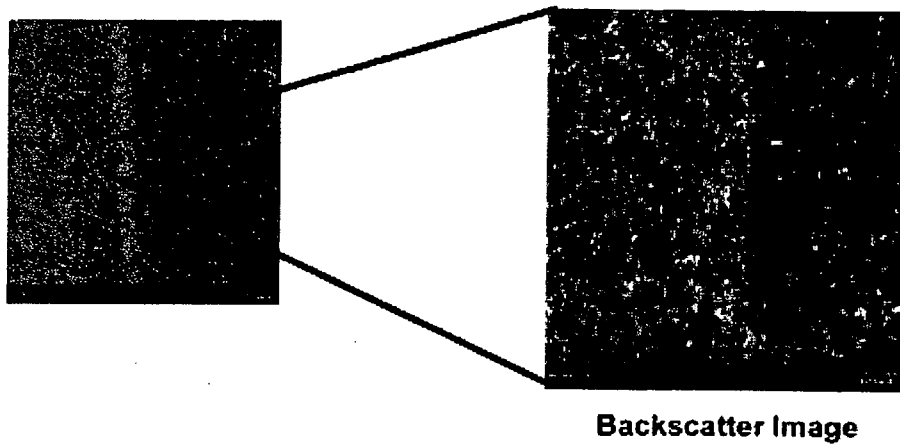
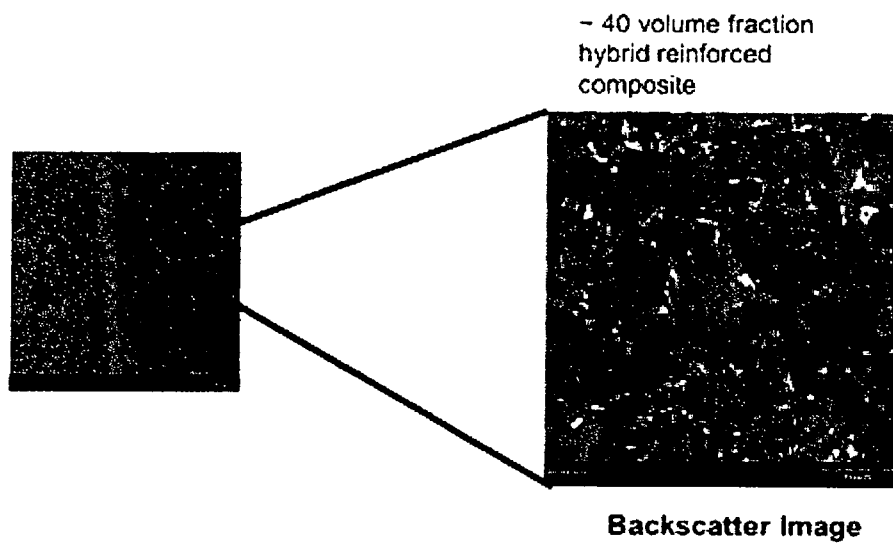
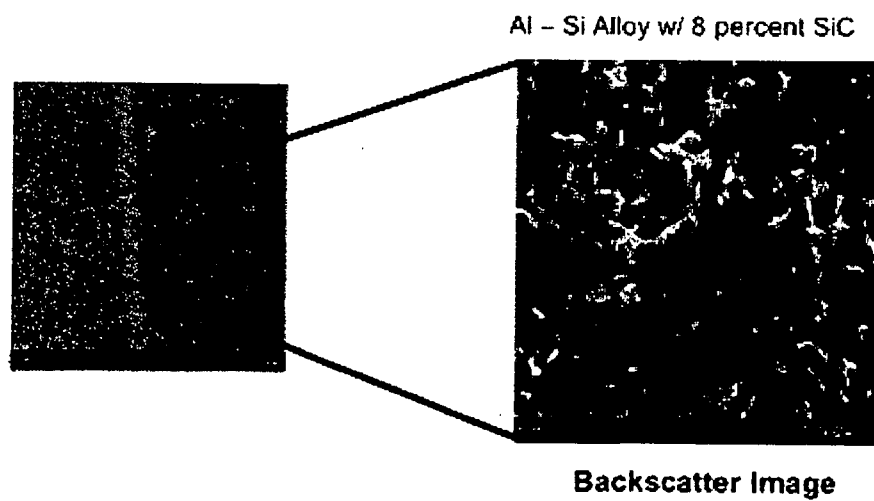


Fig. 4B

Fig. 4C



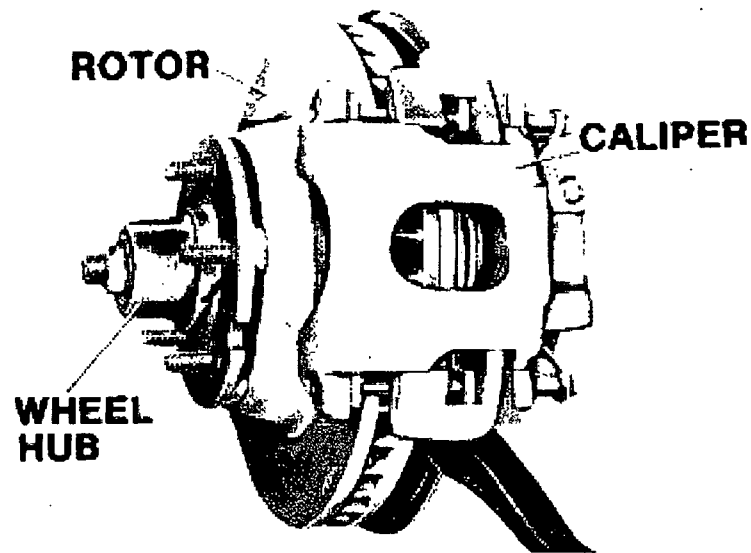


Fig. 5

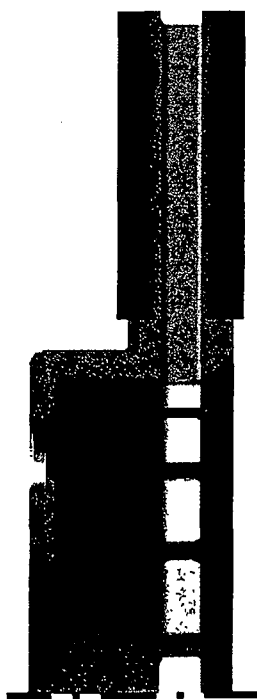


Fig. 6

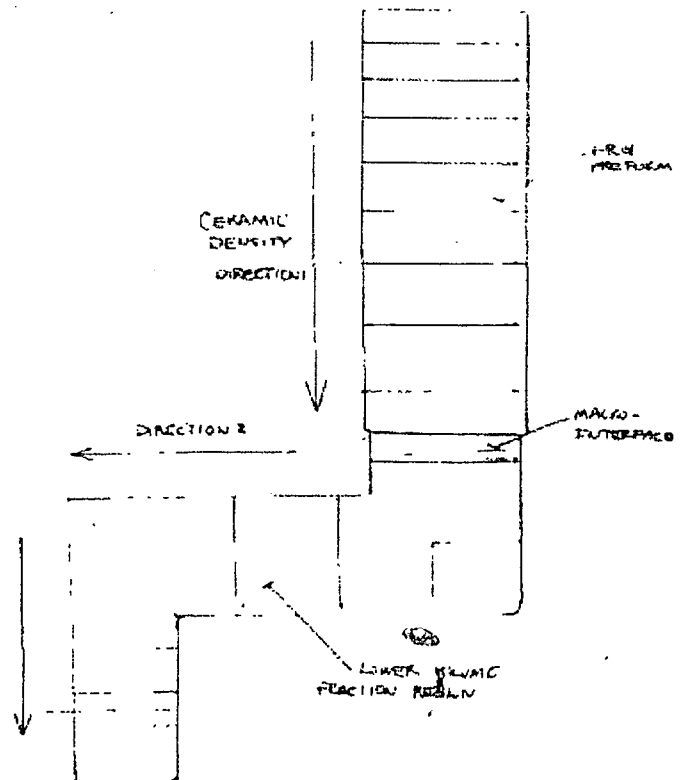


Fig. 7

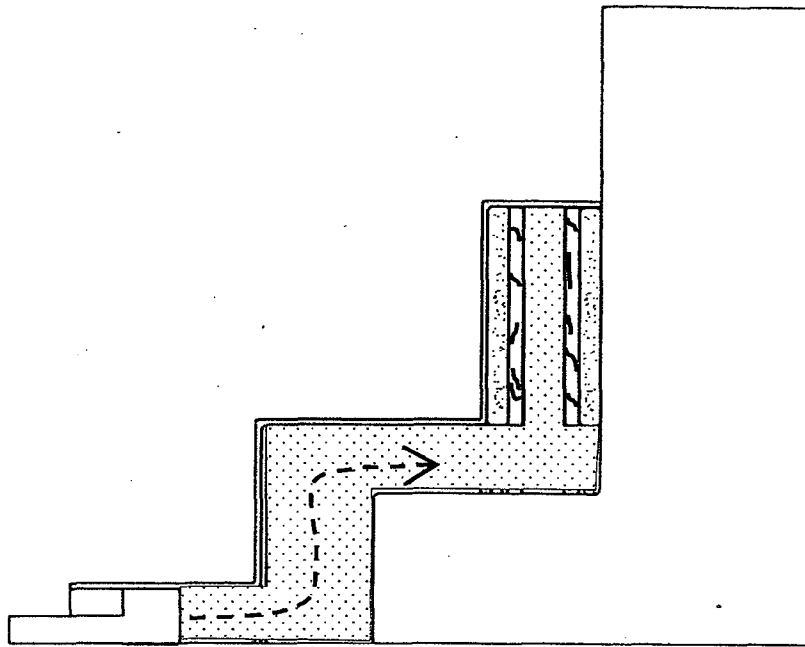


Fig. 8D

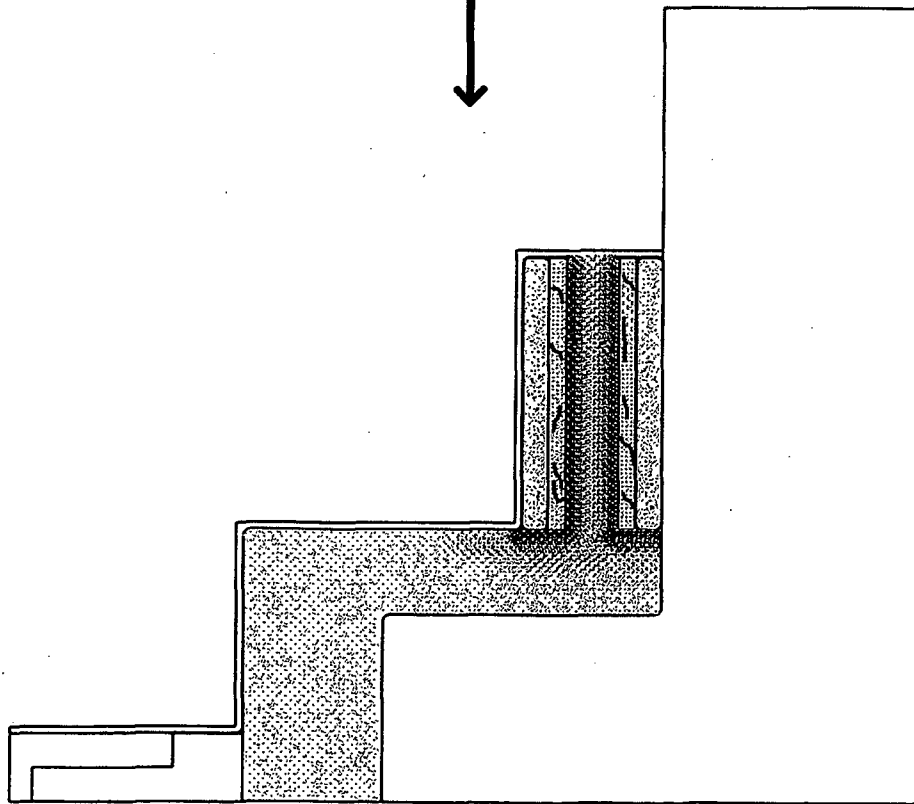


Fig. 8E

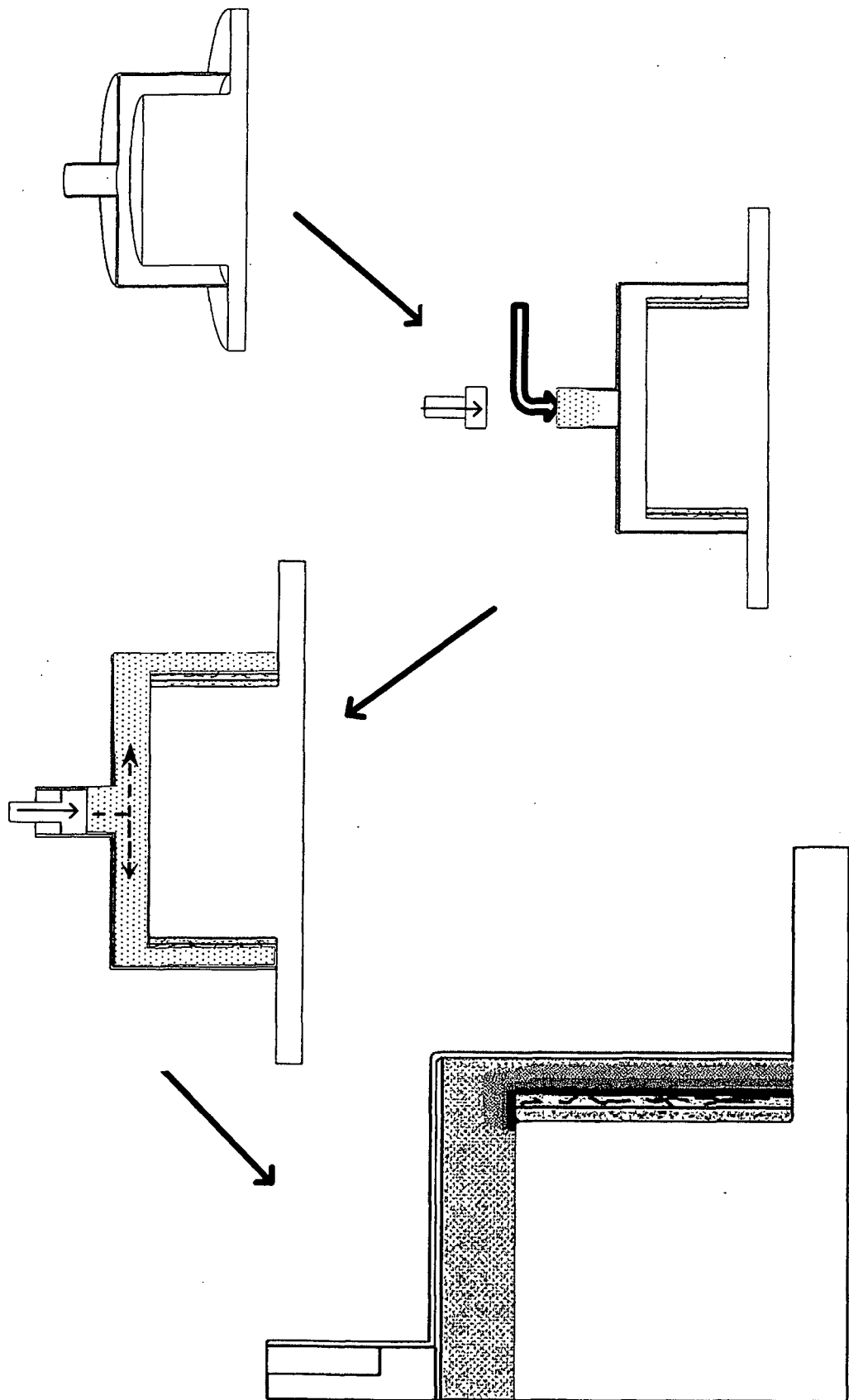


Fig. 9

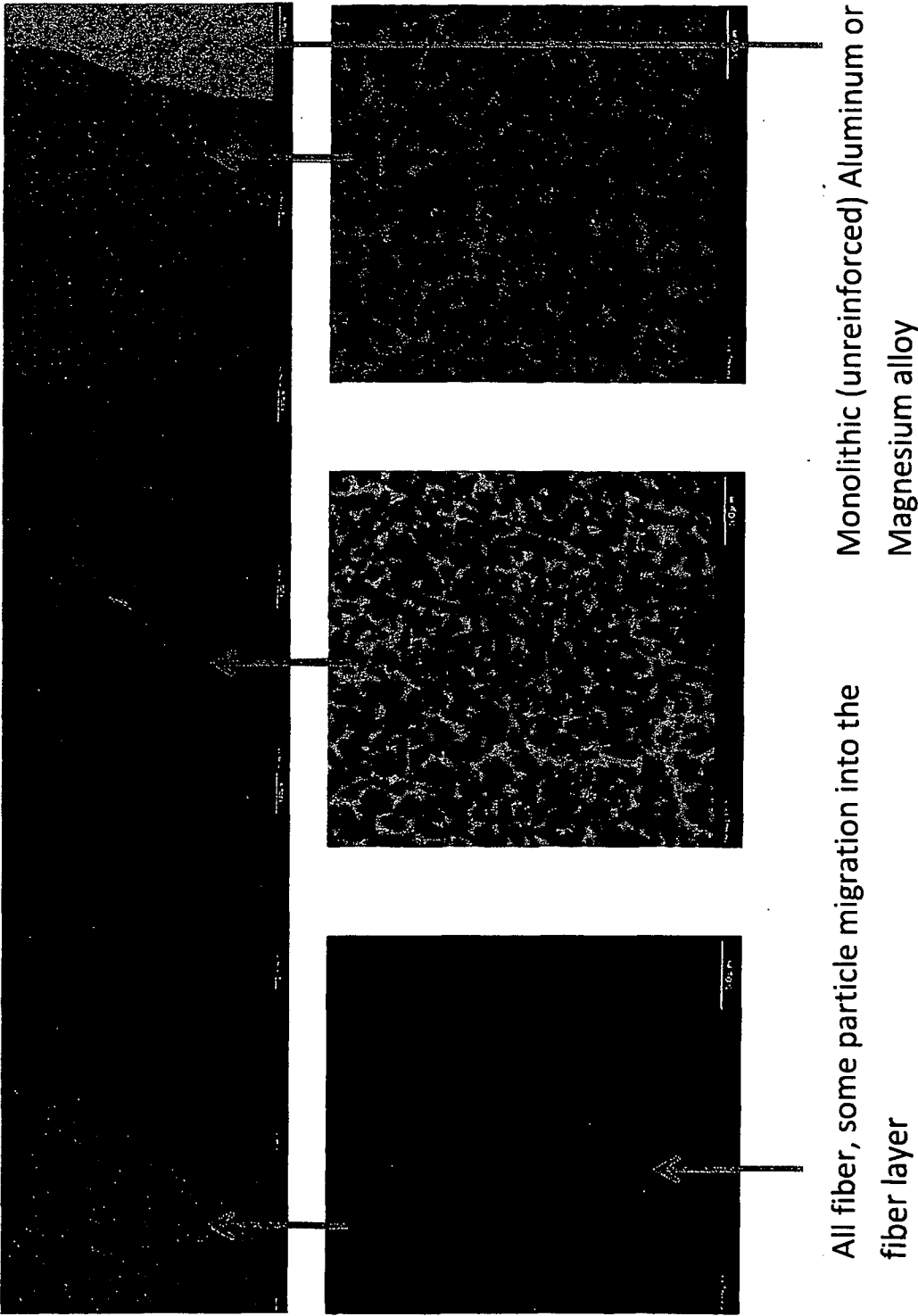


Fig. 10

Fig. 11A

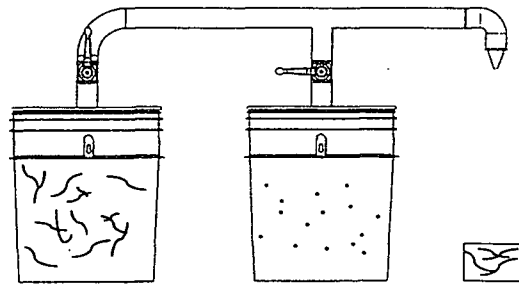


Fig. 11B

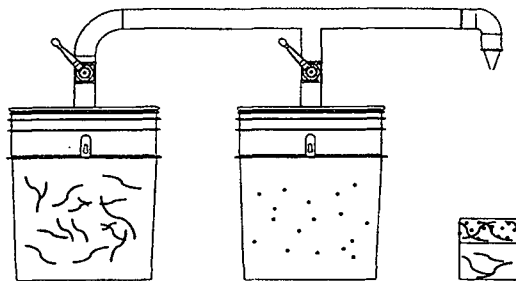


Fig. 11C

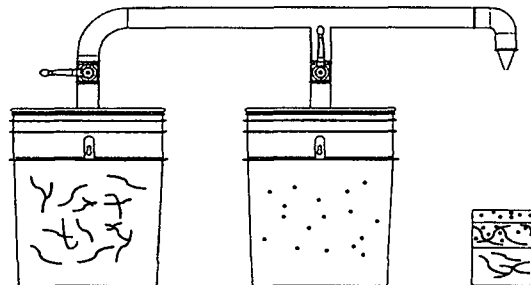


Fig. 11D

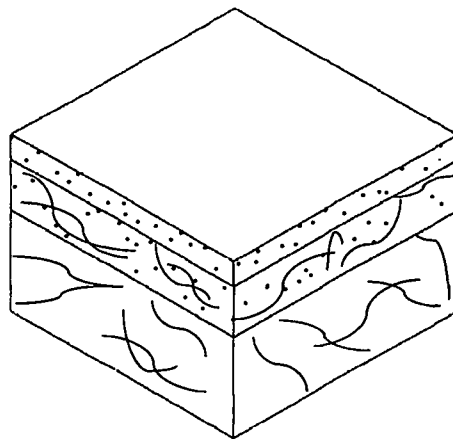


Fig. 12

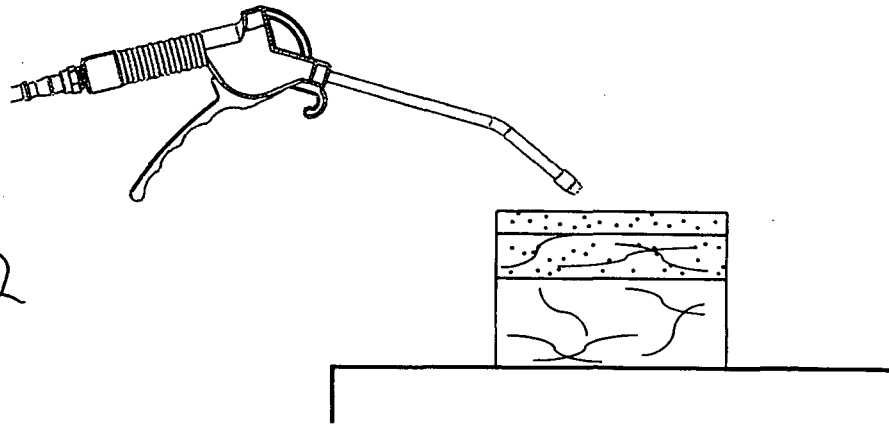


Fig. 13

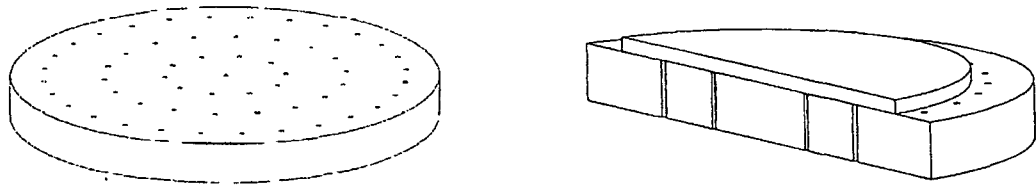


Fig. 14

