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Production of metal matrix composites.

A method of producing a composite cast article having a metal matrix containing divided dispersible solid material, i.e. divided solid filler, such as reinforcing fibres or particles, including the steps of stacking alternating layers (16) of initially solid metal and the dispersible solid (18) in a mold or die (10) having a wall laterally surrounding the stack; heating the wall to raise the temperature of the metal layers (16) above the liquidus, thereby to melt the metal in the stack; and exerting axially directed pressure on the stack to force the molten metal into the layer or layers (18) of dispersible solid, while solidifying the metal by controlling heat flow in such a manner that a solidification front advances unidirectionally, along the cavity axis, entirely through the or each metal-infiltrated filler layer.

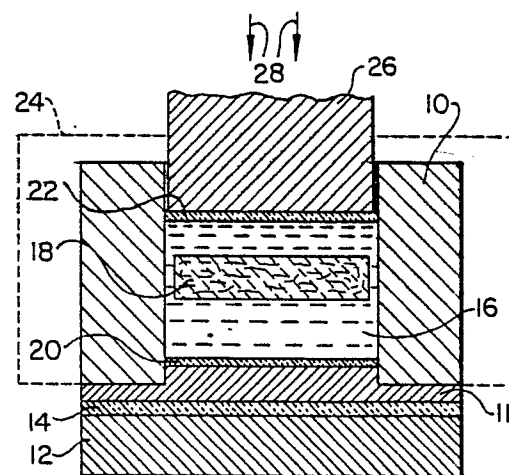


FIG. 1

"PRODUCTION OF METAL MATRIX COMPOSITES"

This invention relates to the production of metal matrix composites, and more particularly to
5. methods of producing cast metal matrix composite articles, as well as to the products of such methods.

Metal matrix composites are articles constituted of a metal matrix, e.g. aluminium or alloys thereof, having distributed therein a divided solid
10 filler, viz. a fibrous or particulate material which is capable of being incorporated in and distributed through such metal matrix and which at least substantially maintains its integrity as thus incorporated rather than losing its form or identity by dissolution
15 in or chemical combination with the metal.

In Japanese patent publication No. 58-204139, there is described a procedure for forming composites in which alternating layers of reinforcing fibres and aluminium foil are set between male and female molds,
20 heated to "melt" the foil, and subjected to relatively light pressure to form an integrated composite. This procedure, however, is not suitable for the production of ingots having substantial bulk or thickness, at least when discontinuous reinforcing fibres are
25 employed. In such case, a large number of individual foil layers would be necessary, each having surface oxide films, and the presence of oxide would prevent attainment of desired product properties. Moreover, in the production of bulky composite ingots, it is
30 difficult to determine the proper amount of metal to be provided; too much or too little metal results in an unacceptably nonuniform product.

It has also been proposed, for example in U.S. patent No. 3,970,136, to arrange a stack of alternating
35 sheets of fibrous reinforcement and matrix metal (in solid state), and then to heat the stack and melt the

metal, applying pressure when the metal is molten to effect infiltration of the metal into the fibre layers. With procedures of this type as heretofore known, however, difficulty has been encountered in that

5 (especially where the fibre layers are of appreciable thickness) the produced composites tend to have porous zones exhibiting poor mechanical properties. Also, these techniques have been limited as to the configurations of fibre-reinforced zones that can be produced.

10 The present invention provides a new and improved method of producing a composite cast article comprising a metal matrix and a divided solid filler incorporated in and distributed through the whole or at least a desired region of the matrix. At least one
15 layer comprising a preform of a divided solid filler and a melt of the metal matrix are provided in a die cavity and pressure is exerted thereon in a direction parallel to the cavity axis for forcing the molten metal to fully infiltrate the preform filler, after which the
20 resultant cast article is solidified. One embodiment includes the steps of disposing at least one layer comprising a preform of a divided solid filler and at least two layers of initially solid matrix metal as a stack, with the filler layer between the metal layers,
25 in a cavity defined by a die wall laterally surrounding the stack, the cavity having an axis extending through all the layers of the stack; heating the die wall for raising the temperature of the matrix metal in the stack above the liquidus of the metal, thereby to melt
30 fully the matrix metal in the stack; and thereupon exerting pressure on the stack in a direction parallel to the cavity axis, for forcing the molten metal to fully infiltrate or impregnate the preform filler layer, while solidifying the infiltrating metal. In
35 another embodiment, the preform filler may be infiltrated with molten metal by pushing the preform through

molten metal in the die cavity. As used herein, the term "preform" refers to an effectively integral, porous compacted body of divided solid filler fibres or particles which has been subjected to sufficient compacting pressure to develop green strength, viz. strength such that the compacted body is self-sustaining in shape and dimensions when handled.

According to the novel feature, the solidifying step is performed by controlling heat flow within the die cavity in such manner that a solidification front advances unidirectionally, along the cavity axis, entirely through the metal-infiltrated preform layer, while the metal ahead of this front within and at least immediately beyond the preform layer remains molten; and the metal layer disposed beyond the preform layer (with respect to the direction of advance of the aforementioned solidification front) contains metal in excess of the amount which infiltrates the preform from that metal layer during the pressure-exerting step. It is found that this combination of features enables production of composite articles which are advantageously free of porous zones and which, in consequence, are characterised by fully adequate mechanical properties throughout.

In procedures as previously proposed for producing fibre-reinforced or like metal matrix composites by heating and pressing a stack of alternating metal and fibre layers, convergent solidification fronts tend to meet within a metal-impregnated fibre layer. At their junction, owing to concentration of the solidifying metal, a porous zone is created; and since this zone is bounded on both sides by solidification fronts, no continuing supply of molten metal is available to fill the pores. As a result, the porous zone remains unfilled and weakens the produced composite. With the method of the present invention, however, contraction-

created pores cannot be enclosed between converging solidification fronts in a filler layer because there is only a single solidification front advancing unidirectionally through the entire preform layer; and
5 ahead of this front there is a continuing supply of molten metal, which fills any contraction-vacated space, under the continuing applied infiltration pressure.

The requisite control of heat flow within the
10 die cavity during the pressure-exerting step is effected, in currently preferred embodiments of the invention, by establishing a temperature differential between opposite ends of the die cavity, as for example by selectively heating or cooling one end of the die;
15 by selectively thermally insulating one end of the die, so that heat is preferentially transferred from the other end of the cavity; or by an appropriate combination of these techniques. With such a temperature differential, two opposed solidification fronts may
20 nevertheless advance toward each other along the cavity axis from the opposite ends of the cavity, but with different initiation times and/or rates of advance, so that they meet within the zone or layer of excess metal beyond the preform layer rather than within the preform
25 layer itself, and only one of the solidification fronts passes through the preform.

The heating step may be performed concurrently with the pressure-exerting step by moving an external source of heat (for melting the matrix metal) progressively and unidirectionally along the die from one end
30 of the die to the other and parallel to the axis thereof as infiltrating pressure is exerted endwise on the metal-preform stack within the cavity. A unidirectionally advancing solidification front, in this
35 case, follows the heat source along the cavity axis. This is particularly convenient for producing a comp-

osite article from a stack containing a plurality of filler preforms alternating with matrix metal layers, as may be advantageous to form an article of substantial axial length.

5 Each layer of the matrix metal is preferably an integral unitary continuous body of the metal at least about 2.5 mm thick, and the preform is also at least about 2.5 mm thick.

Further features and advantages of the
10 invention will be apparent from the detailed description hereinbelow set forth, together with the accompanying drawings:-

Figure 1 is a schematic sectional elevational view of a die for carrying out the method of the
15 invention;

Figure 2 is a view similar to Figure 1 in illustration of the practice of the present method to produce a composite article of annular shape; and

Figure 3 is a schematic sectional elevational
20 view of a die containing multiple layers.

For purposes of illustration, the invention will be described as embodied in methods of producing cast composite billets of aluminium (matrix metal) and discontinuous reinforcing fibres of a refractory
25 material such as SiC or Al_2O_3 . Such composites have utility for structural and other purposes, being characterised by light weight and high strength.

Referring now more particularly to Figure 1, there is shown a die 10 fabricated of a suitably
30 thermally conductive material (e.g. steel), defining an axially vertical and upwardly opening cylindrical die cavity having its lower end closed by a metal or like die plate 11. The die plate is supported on a steel base plate 12 and is separated therefrom by a layer 14
35 of compressible thermal insulation, e.g. Fibrefrax^R.

Within the die cavity are disposed a quantity

of matrix metal 16 and a disc-shaped preform 18 of a refractory fibre material which is to be impregnated with the matrix metal to produce a composite metal-fibre article. Examples of suitable fibre materials for the preform include particles of alumina, zirconia, silica, silicon carbide, silicon nitride or titanium diboride, in particular alumina in the form of chopped fibres, and silicon carbide or silicon nitride in the form of either whiskers or chopped fibres.

As initially introduced to the die cavity, the matrix metal comprises two discs of solid metal, with the preform 18 sandwiched between them. The lower of the two matrix metal discs rests on a layer 20 of thermal insulation which in turn rests on the die plate 11, while a further layer 22 of the thermal insulation rests on top of the upper matrix metal disc. Both insulating layers are made of fibrous or like material (e.g. "Fibrefrax" aluminium silicate fibre).

In the practice of the present method, in the embodiment represented by Figure 1, the die is first heated, to melt the matrix metal, e.g. by means of a conventional induction or resistance heater 24 surrounding the die and arranged to minimise heating of the base plate 12. A vertically movable ram 26, positioned in register with the die cavity, is advanced downwardly to bear against the upper insulation layer 22; when the matrix metal has become fully molten, heating is terminated, and the ram is operated to exert pressure in a downward vertical direction (arrows 28) on the contents of the die cavity.

Figure 1 illustrates that point in the performance of the method at which the matrix metal is entirely molten, heating has been discontinued, and the ram has just come into contact with the upper insulation layer 22. Thereafter, pressure exerted by the ram forces the molten matrix metal into the

insulation layers 20 and 22 and the preform 18, and also compresses the insulation layer 14. Preferably, the insulation layers 20 and 22 are of coarser weave than the preform 18, so that these layers become
5 infiltrated in advance of the preform; also preferably, the preform has a compressive strength sufficient to withstand the pressure applied by the ram, and hence substantially retains its initial shape and dimensions.

As the application of pressure continues, with
10 impregnation of the preform, the matrix metal cools and solidifies since heat is no longer being supplied to the system. Finally, the ram is withdrawn upwardly, and the formed composite product may be removed from the die and trimmed to remove the impregnated insul-
15 ation layers 20 and 22 and any excess metal.

In accordance with the invention, when the application of pressure is initiated, a temperature differential is established between the upper and lower ends of the contents of the die cavity. Cooling, and
20 resultant solidification, proceed inwardly in vertical directions from the top and bottom of the die cavity, but owing to the temperature differential, and to the relative initial vertical dimensions of metal above and below the preform and of the preform itself, the
25 advancing upper and lower solidification fronts meet in the metal below the preform rather than within the preform itself. In order that this will occur, it is also necessary to apply and maintain a ram pressure sufficient to achieve complete infiltration of the
30 preform with matrix metal before metal solidification is completed; preferably, a two-stage pressure cycle is employed, including a first, brief period of relatively low pressure (during which the insulation layers 20 and 22 become impregnated with matrix metal) and a second,
35 longer period of substantially higher pressure effective to achieve complete impregnation of the preform 18.

As a result of the aforementioned features of the invention, while the impregnating matrix metal is solidifying within the preform there is a single solidification front proceeding unidirectionally therethrough, so that molten metal is always available to occupy space vacated by contraction of solidifying metal in the preform, i.e. until impregnation and solidification of metal in the preform are complete. In this way, undesired porosity of the produced composite is avoided, and satisfactory mechanical properties are achieved throughout the composite body, even with a composite of substantial thickness.

To achieve the initial temperature differential, in the embodiment of Figure 1, the ram 26 is fabricated of a metal of high thermal conductivity such as die steel (which may also be the material of the base plate 12) or copper bronze and is "cold", i.e. unheated, as introduced to the die cavity; if desired for expedited matrix metal solidification, the ram may be internally cooled, but such positive cooling is not required in all instances. In addition, the die plate 11 is heated by the resistance or induction heater 24 before the ram is introduced, it being noted that the peripheral portion of this plate is in direct contact with the heated die and that the plate is initially well insulated by layer 14 from the relatively unheated base plate 12, so as to minimise heat losses. Thus, as the ram begins to press against the upper end of the die cavity contents, its relatively low temperature, and the relatively high temperature of the die plate 11 at the lower end of the cavity contents, cause the lower end of the cavity to be hotter than the upper end.

Initially, the cool ram abstracts heat from the top end of the die cavity, solidifying metal which has infiltrated the insulation layer 22 (thereby providing

a seal against molten metal leakage) and initiating a first solidification front that moves downwardly through the cavity. When pressure exerted by the ram compresses the insulation layer 14 between the die plate 11 and the base plate 12, reducing the insulating effect of the layer 14 and enhancing the thermal contact between the initially heated die plate and the initially cool base plate, heat is abstracted from the lower end of the die cavity. Thereupon, solidification of the contained metal commences at that locality, sealing any escape paths for molten metal at the bottom of the die and initiating a second, upwardly moving solidification front. The effect of the initial heat differential between the top and bottom of the die cavity, however, is to retard the upward advance of the second front relative to the downward advance of the first front; hence the fronts ultimately meet at a level, in the cavity, which is substantially below the midpoint between their respective starting levels.

The relative thicknesses of the metal above the preform, the preform itself, and the metal below the preform are so chosen that the two solidification fronts thus respectively advancing from the upper and lower ends of the cavity meet below the preform, viz. in the lower of the two layers of matrix metal. To this end, in general, the initial thickness of matrix metal below the preform may be selected to be roughly about twice the initial thickness of matrix metal above the preform. More particularly, in the embodiment of Figure 1, it is at present preferred that the initial vertical thickness Y of the matrix metal above the preform (i.e. before application of pressure) be given by the relation

$$Y = (Z/Q) + I,$$

where Z is the initial vertical thickness of the matrix

metal below the preform, Q is a value between about 1.8 and about 2.0 (most preferably about 1.9), and I is the thickness of the insulation layer 22; and that the value of Z be equal to or greater than 0.5 times the vertical thickness of the preform 18 (Z preferably being about equal to the preform thickness). The preform preferably has a thickness of no more than 25 mm in order to assure rapid heating of the fibres.

The lower metal layer thickness Z is sufficient so that, when impregnation of the preform is complete, there will remain a layer of excess metal below the preform in which the solidification fronts can meet. The provision of excess molten metal in the pool below the preform is important to ensure a continuing supply of molten metal for infiltration of the preform at all times as the first solidification front advances downwardly through the preform.

By way of specific illustration, in an example of apparatus as shown in Figure 1 the die 10 has a wall thickness of 25 mm and an internal diameter of about 75 mm, this being also the approximate diameter of the ram 26, which however can enter the die cavity with slight clearance. The central portion of the die plate 11 has a vertical thickness of 6 mm, and its thinner edge portion has a vertical thickness of 3 mm, while the base plate 12 has a vertical thickness of 25 mm. Both the base plate and the ram are fabricated of die steel. The insulating layers are constituted of "Fibrefrax" refractory fibres; layer 14 has an uncompressed vertical thickness of 3 mm, and the vertical thickness of each of layers 20 and 22 is 1.5 mm. The heater 24 is a resistance heater.

In specific instances of use of this exemplary apparatus to practice the present method for producing a disc-shaped metal-fibre composite article having a diameter of 70 mm and a vertical thickness of 30 mm, a

refractory fibre preform 18 of those dimensions is placed in the die cavity between lower and upper solid discs of a suitable aluminium alloy as matrix metal. The vertical thickness Z of matrix metal below the preform is 30 mm, while the vertical thickness Y of matrix metal above the preform is 17 mm. A two-step ram pressure cycle is used, comprising 5 seconds at 21 kg/sq.cm and 240 seconds at 211 kg/sq.cm.

With the foregoing dimensions and conditions, and with preforms respectively having volume fractions of fibres (V_f) equal to 0.10, 0.15 and 0.20, satisfactory composites have been produced (a) using an Al - 12% Si alloy as matrix metal, and heating the die to 600°C, and (b) using an Al - 2% Si alloy as the matrix metal and heating to 660°C. At these die temperatures, the base plate temperature is about 200°C.

Figure 2 illustrates the same apparatus as Figure 1 as used to produce a disc shaped metal article having an annular fibre - reinforced region. For this purpose, in place of the disc-shaped preform of Figure 1, there is provided an annular preform 18a of refractory fibre material. The central hole of the preform is initially filled with a slug of the matrix metal. The annular preform, with its central slug, is placed in the cavity of die 10 between solid upper and lower discs 16a and 16b of matrix metal to form a vertical stack, the metal discs having relative vertical thicknesses Y and Z as defined in relation to the vertical thickness of the preform; and the method of the invention is performed in the manner described above with reference to Figure 1, to produce the desired composite article. In this instance, as the upper metal disc 16a melts, the molten metal flows around the outer surface of the preform and, together with the metal of the slug 18f, infiltrates the preform

laterally; hence, in the final article, there is a central fibre-free metal region surrounded concentrically by a fibre-reinforced ring and a peripheral zone of fibre-free metal.

5 In a specific example of operation as shown in Figure 2, the preform annulus has a vertical thickness of 45 mm, an outer diameter of 60 mm, and an inner diameter of 30 mm. Metal thicknesses of Y and Z are, respectively, 25 mm and 45 mm. All other dimensions
10 are as given for the example described above with reference to Figure 1. A satisfactory composite has been produced using a preform with $V_f = 0.15$, an Al - 12% Si alloy as matrix metal, a die temperature of 600°C, and a pressure cycle of 5 seconds at 21 kg/sq.cm
15 and 240 seconds at 211 kg/sq.cm.

 An alternative embodiment of the method of the invention is illustrated in Figure 3. As there shown, since it is ordinarily preferred that the thickness of the fibre layer not exceed about 25 mm, a plurality of
20 fibre layers 118a, 118b, 118c, 118d, 118e (each being a single, effectively integral preform at least about 2.5 mm thick), and a plurality of metal layers 116a, 116b, 116c, 116d, 116e (each being a single, integral body of the metal at least about 2.5 mm thick) alternating with
25 and contiguous to the fibre layers, are employed to build up a stack when it is desired to produce a cast composite of substantial axial length.

 Referring further to Figure 3, the stack of multiple layers each of fibre and metal is placed in an
30 axially vertical cylindrical cavity (closed below by a plug 11') of a die 10' generally similar to the die 10 of Figures 1 and 2, and, as in the embodiments of Figures 1 and 2, is subjected to heat and pressure, to raise the temperature of the metal layers above the
35 liquidus of the metal, thereby to melt the metal (with essentially simultaneous heating of the fibres), and to

consolidate the stack. In the embodiment of Figure 3, heat is supplied to the die by an axially short heat source (shown diagrammatically at 24') surrounding the die wall and axially movable relative thereto. During the heating operation, the heat source 24' is advanced progressively from the lower end to the upper end of the stack of fibre and metal layers in the die while pressure is applied endwise to the stack, in an axial direction (arrow 28'), by a ram 26'. The moving heat source 24' successively melts the metal layers 116a, 116b, etc., at the same time heating the fibres, and the pressure exerted by the ram causes the metal, when molten, to infiltrate the heated layers of fibres. A unidirectional solidification front follows the heat source upwardly through the stack, thereby providing the advantages of the invention with respect to avoidance of porous zones in the produced composite.

The localised, progressive heating performed in the embodiment of Figure 3 also facilitates expulsion of air and gas from the fibre layers as infiltration proceeds. If gas entrapment is a particular problem in specific operations, and/or if special precautions are desirable or necessary to minimise oxidation, the die can be evacuated in known manner, as mentioned above.

It will be appreciated that except for the provision of a plurality of layers each of fibre and of metal, and the use of the described directional, progressive heating as the way of controlling heat flow to achieve advance of a single solidification front unidirectionally through the entirety of the thickness of the plural fibre layers, the embodiment of the invention illustrated in Figure 3 is generally similar to those of Figures 1 and 2. The method of Figure 3 enables production of billets or other cast articles of quite substantial size, unconstrained by limitations on

the maximum easily infiltratable thickness of a single fibre layer.

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CLAIMS

1. A method of producing a composite cast article comprising a metal matrix and a divided solid filler incorporated in and distributed through the matrix, wherein at least one layer comprising a preform (18) of a divided solid filler and a melt of the metal matrix (16) are placed in a die cavity and pressure is exerted in a direction parallel to the cavity axis for forcing the molten metal to fully infiltrate the preform filler (18), and the resultant cast article is solidified, characterized in that the infiltrating metal is solidified by controlling heat flow within the die cavity in such manner that a solidification front advances unidirectionally, along the cavity axis, entirely through the metal-infiltrated preform layer, while the metal ahead of this front within and at least immediately beyond the preform layer remains molten.

2. A method according to claim 1 wherein the infiltration of the preform filler layer comprises the steps of: (a) disposing at least one layer comprising a preform (18) of a divided solid filler and at least two layers of initially solid matrix metal (16) as a stack, with the filler layer (18) between the metal layers (16), in a cavity defined by a die wall (10) laterally surrounding the stack, the cavity having an axis extending through all the layers of the stack; (b) heating the die wall (10) for raising temperature of the matrix metal (16) in the stack above the liquidus of the metal, thereby to melt fully the matrix metal in the stack; (c) thereupon exerting pressure on the stack in a direction parallel to the cavity axis, for forcing the molten metal to fully infiltrate the preform filler layer (18), and (d) solidifying the resultant cast article, and the method is further characterized in that the metal layer disposed beyond the preform layer contains metal in excess of the

amount which infiltrates the preform from that metal layer during the pressure-exerting step.

3. A method according to claim 1 or 2, characterized in that the step of controlling heat flow comprises establishing a temperature differential between opposite ends of the die cavity such that one end region of the die cavity is at a higher temperature than the other, and wherein said excess-metal-containing layer is disposed between said preform layer (18) and the higher-temperature end of the die cavity.

4. A method according to claim 3, characterized in that the step of establishing a temperature differential comprises selectively heating one end of the die.

5. A method according to claim 3, characterized in that the step of establishing a temperature differential comprises selectively cooling one end of the die.

6. A method according to claim 3, characterized in that the step of establishing a temperature differential comprises selectively thermally insulating one end of the die (10) such that heat is preferentially abstracted from the die cavity at the other end of the die.

7. A method according to claim 6, characterized in that the pressure-exerting step is performed by a ram (26) introduced to the die cavity at said other end of the die (10), and wherein said ram (26) is at a low temperature relative to said other end of the die (10) and is fabricated of a highly thermally conductive material.

8. A method according to claim 1 or 2, characterized in that said preform (18) is of generally annular configuration (18a) with a central hole coaxial with the stack, and includes a slug (18f) of said matrix metal disposed within said hole.

9. A method according to claim 8, characterized in that said preform (18) has an external diameter substantially smaller than the diameter of said die cavity such that molten metal infiltrates the preform both laterally

and endwise during the pressure-exerting step.

10. A method according to claim 1 or 2, characterized in that said matrix metal is aluminum and said filler comprises reinforcing refractory fibers.

5 11. A method according to claim 2, characterized in that the heating step is performed concurrently with the pressure-exerting step by moving an external source of heat progressively and unidirectionally along the die (10) parallel to said axis, thereby also controlling heat flow
10 within the die cavity such that a solidification front advances, in following relation to the heat source, progressively and unidirectionally along said axis within the die cavity.

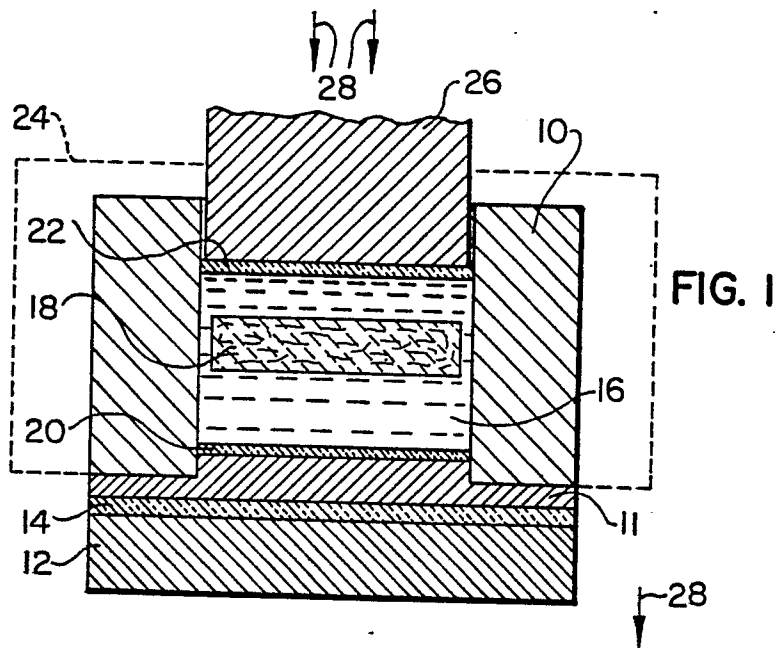


FIG. 2

