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(71) Applicant (*for all designated States except US*): **THE TECHNOLOGY PARTNERSHIP PLC.** [GB/GB]; Melbourn Science Park, Melbourn, Royston, Herts SG8 6EE (GB).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): **HYDE, Samuel, Charles, William** [GB/GB]; 66 Girton Road, Girton, Cambridge CB3 0LN (GB). **GRIFFIN, Neil** [GB/GB]; 62 Ditton Lane, Cambridge CB5 8SR (GB). **CLARKE, Roger** [GB/GB]; 16 Bosworth Road, Cambridge, CB1 8RG (GB).

(74) Agent: **GILL JENNINGS & EVERY**; Broadgate House, 7 Eldon Street, London EC2M 7LH (GB).

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(54) Title: MICROSTRUCTURES AND METHODS OF MANUFACTURING THE SAME

(57) Abstract: A method of forming a plurality of optical microstructures is disclosed. The method includes laser machining a plurality of holes onto a surface and electrolytically polishing at least the holes to remove debris created during the laser machining. Each hole at least partially defines a respective one of the optical microstructures.

WO 2006/046058 A2

MICROSTRUCTURES AND METHODS OF MANUFACTURING THE SAME

The present invention relates to method of manufacturing microstructures, particularly optical microstructures, as well as to microstructures manufactured according to those methods.

The methods have been devised particularly, though by no means solely, for microlens array fabrication.

Throughout this specification, the term optical microstructure' will be understood to refer to any microstructure with an optically functional surface, Le. a microstructure with surfaces having a roughness (Ra) compatible with optical functions, which typically means substantially less than the wavelength of the light that will be incident upon that surface during normal use of the microstructure ('optically-smooth').

Optical microstructures may be final products, such as microlenses, micromirrors or non-imaging concentrators, or provided on items used for producing such products, such as a tool for forming microlenses and, in particular, a seamless roller for producing a large number of microlenses, as will be described further below.

Traditionally, optical microstructures have typically been fabricated using either mechanical or lithographic means.

Mechanical fabrication methods include diamond turning, where either plastics and glass can be directly machined using a diamond tool; or alternatively a mould tool can be machined and optical parts made from the mould tool (see for example the following reference: *Application of Precision Diamond Machining to the Manufacture of Micmphotonics Components;* Davies, Matthew A et al.; published in Proceedings of SPIE, Volume 5153, 2003, pages 94-108).

There are several disadvantages of these mechanical methods, including the limited flexibility of the shapes that are achievable. In particular, complex 3D shapes are difficult to obtain. Moreover, it is not possible to produce patterns that are small in size, with features below 100 micron being difficult to achieve. A further disadvantage is that soft materials, e.g. copper, must be employed to ensure good quality machining, but such materials are more prone to damage and premature wear in particular applications.

Lithographic fabrication techniques involve patterning a photoresist and then electroplating the resultant structure to provide a master from which to mould. Such techniques may mitigate some of the above disadvantages. In particular, they enable smaller and more complex structures to be produced (see for example United States Patent 6071652 "Fabricating optical elements using a photoresist formed from contact printing of a grey level mask" However, there remain limitations in the range of 3D shapes that can be created, and, significantly, lithography can only be used for processing fiat or near-fiat plates of limited size.

There also exists a need for large seamless optical-microstructured surfaces, e.g. for large scale displays. Such surfaces, typically implemented as rollers, are used in reel-to-reel embossing or similar manufacturing processes, where the roller is used to emboss the microstructure onto long reels of plastic or similar materials. It is vital in particular applications that the roller be seamless, in order that long lengths of microstructures without a visible seam can be produced.

Processes such as lithography can be used for fabrication of rollers but the microstructures are created initially fiat (as the process requires) and then wrapped around a roller, thus giving rise to a seam.

Rollers can also be manufactured using mechanical machining methods, such as diamond turning of a copper roller. However, as already described above, this restricts both the type and size of microstructure that can be achieved and the roller material.

There thus exists a need for a precise, reliable and efficient means of manufacturing optical microstructures, which reduces or eliminates the disadvantages described above.

According to a first aspect of the invention, there is provided a method of forming a plurality of optical microstructures in a surface, the method comprising the steps of:

laser machining a plurality of holes into the surface; and

electrolytically polishing at least the holes to remove debris created during the laser machining,

such that each hole at least partially defines a respective one of the plurality optical microstructures.

The term "hole", as used throughout this specification has a broad scope, which will be understood to include any void, region of space or absence of material created in the surface, and thus a feature in that surface, as a result of laser machining.

In a limiting case of the first aspect, there is provided a method of instead forming a single optical microstructure in a surface, the method involving laser machining only a single hole, rather than a plurality of holes, and electrolytically polishing at least the single hole such that it at least partially defines the optical microstructure.

According to a second aspect of the invention, there is provided a method of forming a plurality of microstructures around a curved surface having a central longitudinal axis, the method comprising;

laser machining at least one hole on the projection of a fixed imaginary line onto the surface whilst the surface is in a first angular orientation about the longitudinal axis, the imaginary line being parallel to the longitudinal axis; and

laser machining at least one hole on the projection of the fixed imaginary line onto the surface whilst the surface is in a second angular orientation about the longitudinal axis,

such that each hole at least partially defines a respective one of the plurality of microstructures.

The surface may be metallic.

It will, of course, be understood that the surface may be further rotated , about the longitudinal axis, into further angular orientations, and at least one hole laser machined on the projection of the fixed imaginary line onto the surface in each of those further angular orientations, such that each hole at least partially defines a respective one of the plurality microstructures. According to an embodiment of the invention, each hole is formed by successive pulses. According to a preferred feature of that embodiment, the surface is placed into each of its angular orientations more than once, each time a respective at least one pulse being applied on the projection of the fixed imaginary line to form the or each hole.

According to a third aspect of the invention, there is provided a method of electrolytically polishing a curved surface which has a central longitudinal axis, the method comprising:

rendering the surface an anode;

positioning a narrow cathode in the electrolyte to be closely adjacent the surface and to extend substantially along the length of the surface;

rotating the surface about its longitudinal axis whilst keeping it closely adjacent the cathode, such that, at any given time, the portion of the surface which is closely adjacent the cathode is submerged in the electrolyte.

The surface may be metallic.

The invention, in particular aspects, addresses particular drawbacks as outlined above by combining laser micro-machining with an electro-polishing post process to result in optically-smooth surfaces. By careful control of the laser machining parameters and the post processing, complex optical microstructures such as microlens arrays can be created in materials such as metals of any size, and on highly-curved substrates.

According to one embodiment of the invention, there is provided a method of manufacturing a seamless roller containing one or more optical microstructures for example in an array. An example of a product that will derive benefits from such a roller is a display such as liquid crystal display or front- or rear-projection display. Such displays typically comprise large sheets of optical microstructures such as microlenses or other optical microstructures for use, for example, for control of backlighting, contrast or viewing angles.

Significantly, laser machining allows microstructuring on curved or other surfaces and is thus particularly suited for the production of a seamless roller containing one or more optical microstructures.

The laser machining method of the present invention preferably involves controlling the shape and quality of the resultant microstructures, in order to create a specific remaining surface structure that lends itself to the application of certain electropolishing parameters, thereby allowing the production of microstructure arrays with a well-controlled final profile.

According to a fourth aspect of the invention, there is provided a plurality of optical microstructures formed in accordance with the first aspect.

According to a fifth aspect of the invention, there is provided a plurality of microstructures formed in accordance with the second aspect.

According to a sixth aspect of the invention, there is provided a curved electrolytically polished surface formed in accordance with the third aspect.

Embodiments of the present invention will now be described in detail with reference to the accompanying drawings, in which:

Figure 1 is a perspective view of a portion of a blank from which a mould tool for a microlens array is to be manufactured according a first embodiment of the invention;

Figure 2 is a perspective view of the portion of the blank comprising an array of holes in its surface in accordance with the first embodiment;

Figure 3 is a block diagram of the apparatus 16.

Figure 4a is a cross-sectional view of a hole that has been machined using laser pulse energies that are too low;

Figure 4b is a cross-sectional view of a hole that has been machined using pulse energies that are too high;

Figure 4c is a cross-sectional view of a hole which as been machined using preferred pulse energies;

Figure 5 is a cross-section of a hole, illustrating the transfer of debris onto previously-machined areas;

Figure 6 is a schematic view of a polishing system for a plate;

Figure 7a is a cross-sectional view of a hole after machining but before electrolytic polishing;

Figure 7b is a cross-sectional view of a hole that has been underpolished;

Figure 7c is a cross-sectional view of a hole that has been overpolished;

Figure 7d is a cross-sectional view of a hole/microstructure that has been polished by a preferred amount;

Figure 8 is a schematic view of a polishing system for a cylinder;

Figure 9a is a cross-sectional view of the portion of a blank from which a mould tool for a microlens array is to be manufactured according to a second embodiment;

Figure 9b is a cross-sectional view of the portion of the blank shown in Figure 9a after formation of the holes in its exposed surface, in accordance with the second embodiment;

Figure 9c is a cross-sectional view of the portion of the blank shown in Figure 9b after being subjected to electrolytic polishing, in accordance with the second embodiment;

Figure 9d is a cross-sectional view of a portion of the finished mould tool, in accordance with the second embodiment;

Figure 10a is a cross-sectional view of the portion of a blank from which a mould tool for a microlens array is to be manufactured according to a third embodiment of the invention, after being subjected to electrolytic polishing; and

Figure 10b is a cross-sectional view of a portion of the finished mould tool, in accordance with the third embodiment

Each of the embodiments comprises a method of producing a plurality of optical microstructures and, more particularly, a mould tool for manufacturing an array of microlenses.

The first embodiment lends itself in particular to the production of close-packed holes within the microstructure, for example, a close-packed-hexagonal array. The method of producing a mould tool according to the first embodiment commences with the provision of a blank 10 (see Figure 1) which may be formed as a cylinder (where, for example, the mould tool is to be a roller) or a plate and which is formed of metal. As an example, the plate or roller may be formed of copper, stainless steel, tool steel or another metal.

The blank 10 comprises an exposed surface 12 into which an array of microstructures is to be formed. The exposed surface 12 may already be provided with an optical flat and smooth finish by means of conventional treatment such as precision lapping and/or mechanical/electrolytic polishing.

The dimensions of the surface 12 will vary according to the number, size and spacing of the microstructures in the array.

In the initial step of the method of the first embodiment, an array of holes 14 is produced in the surface 12 by means of laser machining, as depicted in Figure 2. The blank 10 is secured in a laser machining apparatus *16* and the holes 14 are laser machined into the surface 12, as depicted in Figure 2.

The laser machining apparatus 16, as depicted in Figure 3, typically comprises a laser system, an imaging system and a motion-control system, and will be described further below. The apparatus 16 is designed such that at least one controlled laser spot is formed on the surface 12. Multiple laser spots may be advantageous for high speed machining in some cases.

In one example, the laser system comprises a single mode Nd:YVO4 laser 100, with a modulator 102 for self-calibrating intensity. Each hole is produced by a laser beam having a wavelength of 532 nm and provided in pulses with a pulsation frequency of 10kHz and pulse duration of 30ns, the number of pulses and power of the laser are varied according to the required depth of the hole. An alternative laser system could include a Nd:YAG laserwith wavelength of 532nm or 1064nm or an ultrafast Ti:sapphire system.

The imaging system may comprise a simple objective lens to focus the laser beam onto the surface 12. If the motion-control system includes a galvanometer-based beam steering system 103, as is shown in Figure 3, a more complex scan lens arrangement 104 is required. In the example of this embodiment depicted in Figure 3, projection of a shaped aperture mask 106 onto the material is used to control size and shape of the laser spot in two dimensions. A greyscale mask (e.g. a pattern of chrome of variable thickness deposited on glass) may be used to further control the intensity across the spot and to control depth profile of the hole. The mask may alternatively comprise an electronically controllable spatial light modulator to allowthe projected laser spot shape to be modulated. The shape and size of the beam on the surface 12 may be further controlled by moving the focus plane away from the surface 12.

In the example shown in Figure 3, the motion-control system comprises a galvanometer-based laser bench steering system 103 in three Cartesian coordinates (X, Y, Z). The motion-control system may also comprise a precision motion stage to move the blank 10 (as indicated by arrow 108) while keeping the laser focus position fixed or allowing the focus position to move only small distances. This has the advantage of allowing large samples to be prepared, as well as the advantage of simplifying the imaging system and improving its imaging performance.

The laser machining is controlled through process parameters, including beam size, beam shape, pulse energy, number of pulses and pulse sequence. Fine control of these parameters allows the undesirable features arising from the machining process, including roughness and debris, to be kept to a minimum. At the same time, the desirable features, such as surface shape, depth profile and uniformity are controlled to be close to the final desired microstructure.

It is important that the size of the undesirable features is controlled to be smaller than the minimum feature size of the desirable features. When this is achieved, it is possible to remove the undesirable features without destroying the intended features by accurately controlling the subsequent electro-polishing step. Improvements to the laser machining process thus allow a shorter polish step to be employed and consequently, the feature size achievable in the final microstructure is reduced.

When the microstructure array is close-packed, an important aspect of the process control is to prevent modification of microstructures in close proximity to the microstructure being machined, One way in which this is achieved is to control the laser spot using mask projection so that the laser spot does not overlap any other microstructures. For example, in a hexagonal close-packed array, a hexagonal laser spot may be used.

In the example where the laser system is a Nd:YVO4 or a Nd:YAG laser, pulse energy is an important parameter for control of quality as depicted in Figures 4a, 4b and 4c. It has been found that a high energy pulse produces a surface with few undesired artefacts, but creates more debris 17 and in particular, more debris is ejected onto surrounding microstructures (see Figure 4b). A lower energy pulse produces a lower quality surface shape with artefacts, such as ripples, but less debris is produced, and less debris is transferred to adjacent microstructures (see Figure 4a). By choosing the preferred pulse energy, much of the debris collects as a ring 19 around the microstructure being machined, as shown in Figure 4c. In this case, the debris is excluded from the machined microstructures and the ring of debris 19 acts as a barrier, limiting further transfer of debris to adjacent microstructures during subsequent laser pulses.

Typically, the depth of the microstructure is controlled by selecting an appropriate number of pulses. Additional process control may be applied by using pulses with different energy within the pulse sequence. In one example, at least one low energy pulse is employed to remove material from the microstructure with minimal damage to surrounding microstructures, then at least one higher energy pulse is applied to improve the surface finish of the final microstructure. This pulse sequence generates less debris than using all high-energy pulses but achieves a similar surface finish. For example, when machining copper, multiple pulses of approximately 25 J/cm^2 followed by 1 or 2 pulses of approximately 50 J/cm^2 produced good results.

When laser machining is applied to an area contaminated by debris generated through machining of a nearby microstructure, the debris is re-melted and thereby removed. Therefore, when machining an array of microstructures one at a time, each microstructure is contaminated by an accumulation of debris from microstructures machined afterwards, but is not affected by microstructures machined beforehand.

This is depicted in Figure 5. In a further aspect of this invention, the pulse sequence is modified to reduce the build-up of debris and facilitate accurate 3D micromachining of the array.

According to this further aspect, instead of machining a complete microstructure at once, then moving onto the next, the microstructure and its neighbouring microstructures are only partially machined. One or more machining pass across the array is then employed to complete each microstructure. For example, a microstructure that requires eight pulses may be machined by eight passes, each of which applies a single pulse to each microstructure. In this way, debris is removed by subsequent machining passes, and debris on the final microstructure only arises from the final single-pulse pass. An added advantage of applying only one pulse per pass to each microstructure is that machining can take place without the need to stop or compensate for the motion of the sample. Each subsequent machining pass may be carried out after completion of the first pass over the entire surface 12. Alternatively, subsequent passes may commence when only a portion of the first pass is complete. In the second case, the subsequent pass should only be applied to areas of the surface that are outside the area affected by debris from regions not yet processed in the first pass, so that further contamination from the first pass cannot occur.

It is important to ensure that the laser beam incident on the mask has an appropriate intensity profile or that the mask compensates for any deviation from the desired profile. For example, typically a laser beam would have a Gaussian intensity profile and machining would result in a machined microstructure with an approximately Gaussian shaped depth profile. The intensity can be adjusted as described above using a greyscale mask to achieve machined microstructures with desired depth profile. The depth profile of the final structure will be influenced by any non-linear response of the material removal, and by any modifications to the profile resulting from the polish process, so it is important to take account of these effects when selecting the intensity profile.

In the example of the embodiment shown in Figure 8, the blank 10' comprises a seamless cylinder which, for example, may be used to produce a seamless roller into the cylindrical surface of which the microstructure is formed (the electrolytic polishing of the cylindrical surface will be described below). It will be appreciated that, in the case of this example, the portions of the blank depicted in Figures 1 and 2 will have a slight curvature. The forming of the holes 14, in this example, initially involves placing the blank 10' in a first angular orientation and laser machining the surface 12 at positions along the projection of a fixed imaginary line onto the surface 12 in its first angular orientation, thereby creating a column of ablated spots (each ablated spot constituting, or being the precursor to, a hole, depending on whether the holes are to be formed by one or more (respectively) passes of the drill with respect to the surface 12), , the imaginary line being parallel to the longitudinal axis and possibly being defined by an axis 41 (e.g. X-axis) along which the drill 16 may traverse. This may be effected by advancing the cylinder in the direction parallel to its longitudinal axis, between each position, thereby avoiding the need to move the drill 16. The cylinder is then rotated, about its longitudinal axis, into a second angular orientation (as specifically shown in Figure 2) and laser machining is carried out at positions along the projection of a fixed imaginary line onto the surface 12 in its second angular orientation, thereby creating a further column of ablated spots. These steps are repeated until the desired number and arrangement of ablated spots (corresponding to the holes) is created over the surface. Each hole may be produced by a plurality of pulses which are performed in successive passes of the drill 16 with respect to the surface 12, as described above (i.e. successive pulses are not used to machine a single hole but rather to partially machine each of a plurality of holes).

In the example described in the previous paragraph, the ablated spots need not be formed column-by-column but instead row-by-row where the rows are transverse to the columns and extend around the circumference of the blank 10'. This may be achieved by placing the cylinder into its first angular orientation then subjecting the surface to a first pulse, rotating the cylinder into its second angular orientation then subjecting the surface to a second pulse, and continuing the process of subjecting the surface to a respective further pulse in each one of further angular orientations. Following the completion of a row 43, the surface 12 is advanced in the direction of the imaginary line 4lso that the next row 45 can be formed in the same manner. Alternatively the surface 12 may be kept stationary and the drill 16 indexed in the direction of the imaginary line 41 that the next row can be machined. Again, each hole 14 may be produced by a plurality of pulses that are performed in successive passes of the drill 16 relative to the surface 12.

It is to be understood that the spacing of holes in a given row or column may vary. In addition, a given row or column may be offset with respect to a neighbouring row or column. In this way, any arrangement of holes, including for example a hexagonal close-packed array, may be produced. In addition, it is to be understood that a given "row" or "column" may ultimately comprise merely a single hole.

Yet a further alternative method of forming holes in the surface of the cylindrical blank 10' involves moving the surface 12, or instead indexing the drill 16, in the direction of the imaginary line 41 as the blank 10' is rotated, thereby forming the holes in a helix.

In each of the alternative methods of forming the holes, rotating the surface 12 about its longitudinal axis eliminates the need to move the drill 16 around the curved surface 12. Furthermore, advancing the surface in the direction parallel to its longitudinal axis (after forming a given row or a given ablated spot in a column or helix) avoids the need to move the drill.

As already described above, each ablated spot, when subjected to a pulse, will be contaminated by an accumulation of debris from subsequent pulses performed other ablated spots sufficiently close to that ablated spot but is not affected by pulses formed at nearby ablated spots beforehand. It may thus, in particular applications, be preferable, after application of at least one laser beam pulse in creating a hole, to apply similar pulses in creating all other holes (in at least a portion of the surface) as large as the debris field generated, prior to application of subsequent pulses to the first ablated spot. Thus, the holes are produced by at least two passes of the drill 16 with respect to the surface 12.

In any of the methods of forming the holes 14 in the surface of the cylindrical blank 10', each hole could, instead, be produced by a plurality of successive pulses. In this case, to avoid stepping the motion between each hole (which would be slow), a continuous motion could be while employing optics (such as a galvo system) to keep the beam position in the same spot on the blank 10' for all of the pulses applied to that hole.

The blank 10 may be degreased (not shown) or ultrasonically cleaned to remove loose debris following the laser machining prior to electro-polishing.

The surface 12 of the blank 10 is next subjected to electrolytic polishing, as depicted in Figure 6. The machined blank 10 is secured in an electrolytic polishing apparatus 31 and the holesl4 are processed to provide an optically-smooth surface finish.

The electrolytic polishing apparatus 31 comprises an electrolyte 32, a cathode 33 and an electrical contact 34. The blank 10 is positioned in contact with the electrical contact 34 so that the surface to be processed forms the anode. In the example depicted in Figure 6, the blank is a plate and the cathode 34 is chosen to be another plate positioned parallel to the blank 10.

The choice of chemicals and voltages for the electrolytic polishing regime is designed to preferentially remove the fine undesired features remaining after the machining. This may be achieved by selecting a voltage such that a polarised layer is formed in the electrolyte next to the surface 12. This promotes the preferential removal of features that are raised relative to their surroundings, such as debris and small-scale roughness features. The polishing time is chosen to avoid any detrimental impact on the shape, the precise duration being dependent on chemistry and the microstructure. For stainless steel, it is desirable to use perchloric acid-based solution. In the alternative example comprising copper, as referred to above, it is desirable to use phosphoric acid-based solution. Figure 7a shows a microstructure cross-section after machining and before polishing. Figures 7b to 7d illustrate respectively underpolishing, overpolising and a preferred amount of polishing.

In the example involving the cylindrical blank 10' depicted in Figure 8, the cathode 33' is positioned close to the surface of the cylinder. The cathode 33' extends substantially along the length of the cylinder (parallel to its longitudinal axis). In this example, the cathode is of such a size that only a small portion of the cylinder is polished at one time. Uniform polishing of the whole surface of the cylinder is accomplished by rotating the cylinder about its axis while applying the polish current. This approach reduces the current requirements of the system and allows continuous replacement of the electrolyte during the process. In an alternative example, the cathode may completely enclose the cylinder.

Completion of the electro-polishing step gives rise to the finished mould tool. It has been found that an optical surface with an average roughness of Ra 2.5 nm can be achieved using the method according to the invention, where the polishing is carried out for a period of approximately 25 seconds.

In the following description of the second and third embodiments, the same reference numerals will be used to denote common features. The second embodiment is particularly advantageous when the microstructures are not close packed.

The second embodiment comprises the same steps and the same process enhancements as described above in connection with the first embodiment, but it additionally comprises the deposition of a layer 20 of another material on the blank 10 at the beginning of the manufacturing stage, as depicted in Figure 9a. In an example of this embodiment, the substrate metal is stainless steel and the other material is sputtered nickel, which is deposited with a thickness of approximately 1-2μm.

The blank 10 of this embodiment has, prior to deposition of the layer 20, been subjected to the same surface pre-treatment as described in connection with the first embodiment.

The blank 10 is next subjected to laser machining (in a manner the same as that depicted in Figure 2) to produce the array (see Figure 9b), as described in connection with the first embodiment. The microstructures 14 are machined such that they entirely penetrate the layer 20 and continue beyond that layer so as to penetrate partially the blank material covered by that layer.

Following laser machining, the blank 10 is subjected to electrolytic polishing (see Figure 6) in the same manner as described in connection with the first embodiment, to remove the debris/dross 17 (see Figure 9c), the polishing solution, time and voltage being selected as appropriate for the substrate material (in this case, stainless steel).

In the final stage of the manufacturing method according to the second embodiment, the blank is subjected to selective etching, whereby the remaining layer material is selectively removed from the blank 10. In this particular example, the etching comprises chemical etching using 70% nitric acid. Removal of the layer material gives rise to a surface configuration comprising sharp transitions between the holes and the remainder of the surface (see Figure 9d), because the layer 20 has protected those transitions from being eroded and/or otherwise damaged during the laser machining and electrolytic polishing.

A third embodiment of the invention is identical to the second embodiment though does not involve deposition of a different material on the blank, the outer layer 30 instead being integral with, and thus of the same material as, the blank 10. The broken line in Figure ba represents an imaginary line in the material defining the bottom of the layer 30. The outer layer 30 may be the same thickness as the layer 20 of the second embodiment.

In this embodiment, the laser machining of the holes into the surface and electrolytic polishing of the holes is carried out in the same way as for the second embodiment, though, after the electrolytic polishing, the holed surface is precision-lapped, so as to remove an outer layer 30 from the blank 10 (see Figures 10a and l0b).

In the third embodiment, sharp transitions between the holes and the remainder of the surface thus be produced, as described in connection with the second embodiment.

It should be noted that the mould tool produced according to any embodiment can be used for direct moulding of the optical microstructures ('direct replication'), or instead to mould an intermediate replica, from which a corresponding mould tool (e.g. a silicone mould tool) may be produced, that tool subsequently used to mould the microstructure product. In the case where direct replication is employed, a mould release agent, such as Loctite Frekote 770-NC, may be employed in order to ensure clean separation from the master. A mould sealer, such as Loctite Frekote B-IS, may also be employed.

The polymer replica is cured in the mould tool by appropriate means, such as UV treatment in combination with a suitable curing agent such as Ablelux A4031, Ablestick.

Laser micromachining combined with electro-polishing, in accordance with the invention, is thus an effective method of creating optical microstructures and in particular, large-scale seamless moulds with an array of accurately controlled, repeating 3D microstructures. This is achieved by using pulse durations of nano-seconds to femto-seconds (using the Nd:YVO4 laser referred to above or alternatively, for example, Ti:sapphire or Nd:YAG), Moreover, laser micro-machining offers the advantage of being suitable on many different materials, e.g. hard metal alloys like stainless steel which, due to its hard nature is particularly suited for production of mould tools.

CLAIMS

1. A method of forming a plurality of optical microstructures in a surface, the method comprising the steps of:

laser machining a plurality of holes into a surface; and

electrolytically polishing at least the holes to remove debris created during the laser machining,

such that each hole at least partially defines a respective one of the plurality of optical microstructures.

2. A method according to claim 1, wherein the holes are blind holes.

3. A method according to claim 1 or claim 2, wherein the surface is provided on a blank.

4. A method according to any of the preceding claim, wherein the surface is fiat.

5. A method according to any of claims 1 to 3, wherein the surface is curved.

6. A method according to claim 5, wherein the surface is continuous and has a central longitudinal axis

7. A method according to claim 6, wherein the surface has a circular transverse cross section.

8. A method according to claim 7, wherein the surface is cylindrical.

9. A method according to any of claims 6 to 8, wherein the surface is provided on a seamless roller.

10. A method according to any preceding claim, further comprising the step of forming the holes in an array.

11. A method according to claim 10, wherein the array comprises a hexagonal and/or close packed array.

12. A method according to any of the preceding claim, wherein each hole is formed by a plurality of laser beam pulses.

13. A method according to claim, 12 wherein successive laser beam pulses are performed to machine separate holes.

14. A method according to claim 13, wherein, between two pulses performed at a position corresponding to a given hole, pulses are performed at all positions, corresponding to other holes, which are sufficiently close to that position for those subsequent pulses to create debris contaminating that position.

15. A method according to claim 14 wherein the holes are produced in columns on the surface, successive pulses being applied at successive positions along each column in forming the holes in that column; or the holes are produced in rows on the surface, successive pulses being applied at successive positions along each row in forming the holes in that row, the laser beam source being kept stationary whilst the surface is moved to bring the successive positions into the path of the laser beam.

16. A method according to any of claims 12 to 15, wherein each hole is machined by performing at least one low energy pulse followed by at least one high energy pulse.

17. A method according to claim 16, wherein each hole is machined by performing a plurality of low energy pulses followed by a single high energy pulse.

18. A method according to any of claims 12 to 17, further comprising the step of performing, in respect of each hole, at least one initial pulse having an energy which is such that it creates a ring of debris around the hole, and performing at least one subsequent pulse having an energy which is such that the transfer to adjacent areas of debris created thereby is limited as a result of the ring of debris.

19. A method according to any preceding claim, further comprising the step of masking to adjust the laser beam shape and/or intensity profile.

20. A method according to claim 19, wherein the masking comprises greyscale masking.

21. A method according to claim 20, wherein the greyscale masking comprises using chrome of variable thickness deposited on glass.

22. A method according to any of claims 19 to 21, wherein the masking comprises shaped aperture masking.

23. A method according to any preceding claim, comprising controllable spatial light modulation to adjust the laser beam shape and/or intensity profile.

24. A method according to any preceding claim, wherein the laser machining at least partially comprises laser machining with a defocused laser spot.

25. A method according to any preceding claim further comprising the step of degreasing at least the holes prior to electrolytically polishing.

26. A method according to any preceding claim, comprising ultrasonically cleaning at least the holes prior to electrolytically polishing.

27. A method according to any preceding claim, wherein the electrolytic polishing is carried out for a duration selected to achieve an optically smooth surface finish and to maintain the desired microstructure shape.

28. A method according to any preceding claim, wherein the electrolytic polishing comprises the formation of a polarised layer of electrolyte next to the anode.

29. A method according to any preceding claim, further comprising the step of precision lapping the surface, after electrolytically polishing, so as to remove a layer of material, the layer having a thickness that is less than the depth of the holes.

30. A method according to any of the claims 1 to 28, further comprising:

providing the surface on a layer of a first material deposited over a second material;

laser machining the holes to be of a depth exceeding the thickness of the layer; and

selectively removing the remainder of the first material after the electrolytic polishing.

31. A method according to claim 30, wherein the layer has a thickness of approximately 1 to 10 micron.

32. A method according to claim 30 or claim 31, wherein the selective removal of the remainder of the first material comprises selective etching.

33. A method according to any of claims 30 to 32, wherein the first material comprises sputtered nickel.

34. A method according to any of claims 30 to 33, wherein the second material comprises stainless steel.

35. A method according to claim 34, wherein selective etching is performed using approximately 70% nitric acid.

36. A method according to any of claims 30 to 33, wherein the second material comprises copper.

37. A method according to any of claims 1 to 29, wherein the surface comprises stainless steel.

38. A method according to any of claims 1 to 29, wherein the surface comprises copper.

39. A plurality of optical microstructures produced by a method according to any of the preceding claims.

40. A seamless roller comprising a plurality of optical microstructures according to any of claims 10 to 38 as appended to claim 9.

41. A liquid crystal display comprising a plurality of optical microstructures according to claim 39.

42. A plurality of optical microstructures according to claim 39, being a microlens array or a plurality of micromirrors or non-imaging concentrators.

43. A front or rear projection display comprising a plurality of optical microstructures according to claim 39.

44. A method of forming a plurality of microstructures around a curved surface having a central longitudinal axis, the method comprising;

laser machining at least one hole on the projection of a fixed imaginary line onto the surface whilst the surface is in a first angular orientation about the longitudinal axis, the imaginary line being parallel to the longitudinal axis; and

laser machining at least one hole on the projection of the fixed imaginary line onto the surface whilst the surface is in a second angular orientation about the longitudinal axis,

such that each hole at least partially defines a respective one of the plurality of microstructures.

45. A method according to claim 44, wherein each hole is formed by a plurality of laser beam pulses.

46. A method according to claim 45, wherein successive laser beam pulses are performed to machine separate holes.

47. A method according to claim 46 wherein, between two pulses performed at a position corresponding to a given hole, pulses are performed at all positions,

corresponding to other holes, which are sufficiently close to that position for those subsequent pulses to create debris contaminating that position.

48. A method according to any of claims 44 to 47, wherein the microstructures are optical microstructures.

49. A method according to any of claims 44 to 48, wherein the holes are blind holes.

50. A method according to any of claims 44 to 49, the method further comprising the step of electrolytically polishing the surface to remove debris created by the laser machining.

51. A method according to any of claims 44 to 50, wherein the surface is continuous.

52. A method according to any of claims 44 to 51, wherein the surface has a circular transverse cross section.

53. A method according to claim 52, wherein the surface is cylindrical.

54. A method according to claim 53 as appended to claim 51 , wherein the continuous surface is provided on a seamless roller.

55. A seamless roller comprising a plurality of microstructures manufactured using a method according to claim 54.

56. A method of electrolytically polishing a curved surface which has a central longitudinal axis, the method comprising:

rendering the surface an anode;

positioning a narrow cathode in the electrolyte to be closely adjacent the surface and to extend substantially along the length of the surface;

rotating the surface about its longitudinal axis whilst keeping it closely adjacent the cathode, such that, at any given time, the portion of the surface which is closely adjacent the cathode is submerged in the electrolyte.

57. A method of forming a plurality of optical microstructures substantially as herein described.

58. A method of forming a plurality of microstructures around a surface, substantially as herein described.

59. A method of electrolytically polishing a surface substantially as herein described.

60. A plurality of microstructures substantially as herein described with reference to the accompanying drawings.

61. A plurality of optical microstructures substantially as herein described with reference to the accompanying drawings.

FIG. 1

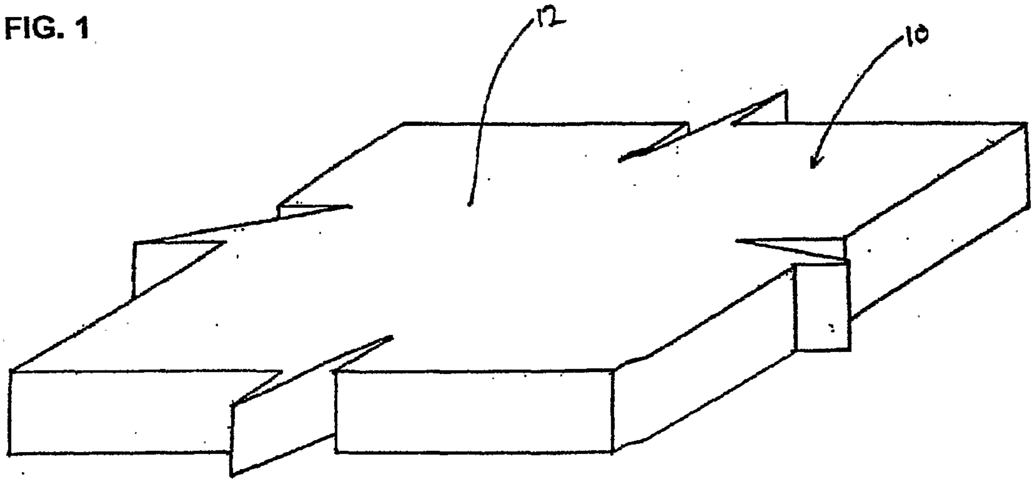

FIG. 2

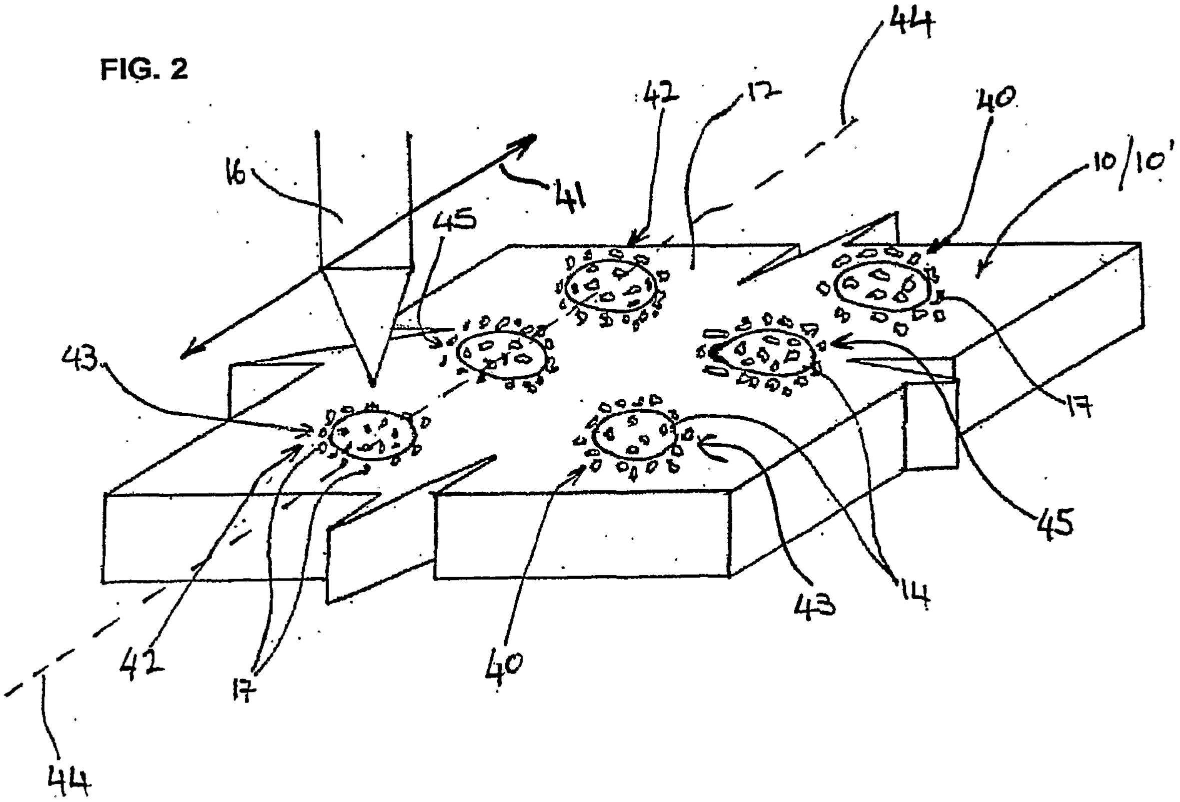

FIG. 3

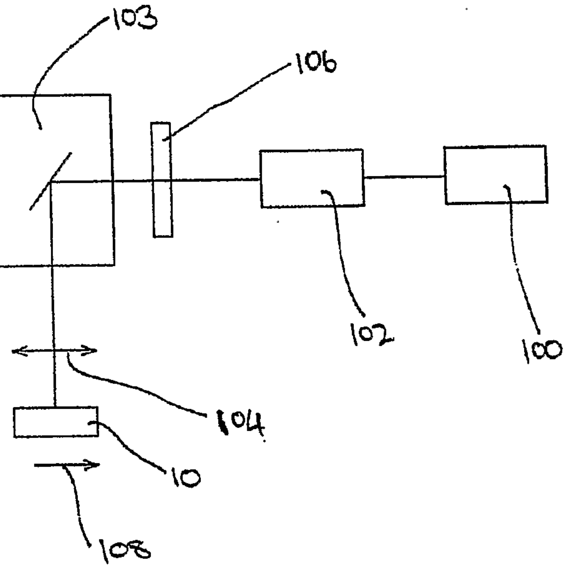

FIG. 4a

FIG. 4b

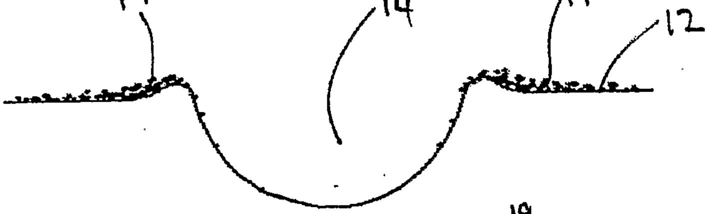

FIG. 4c

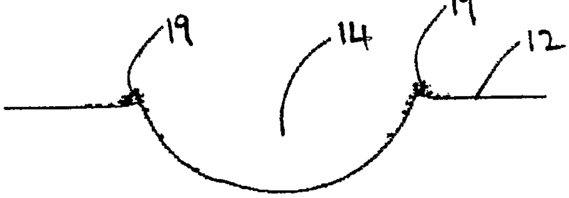

FIG. 5

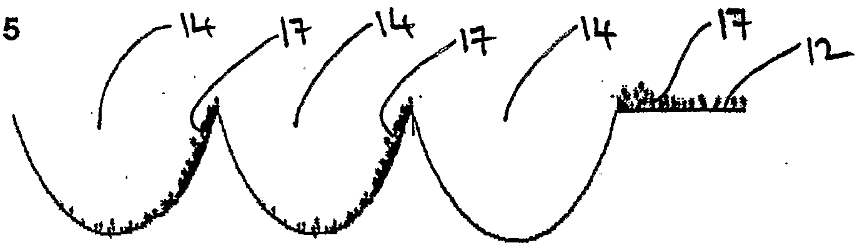

FIG. 6

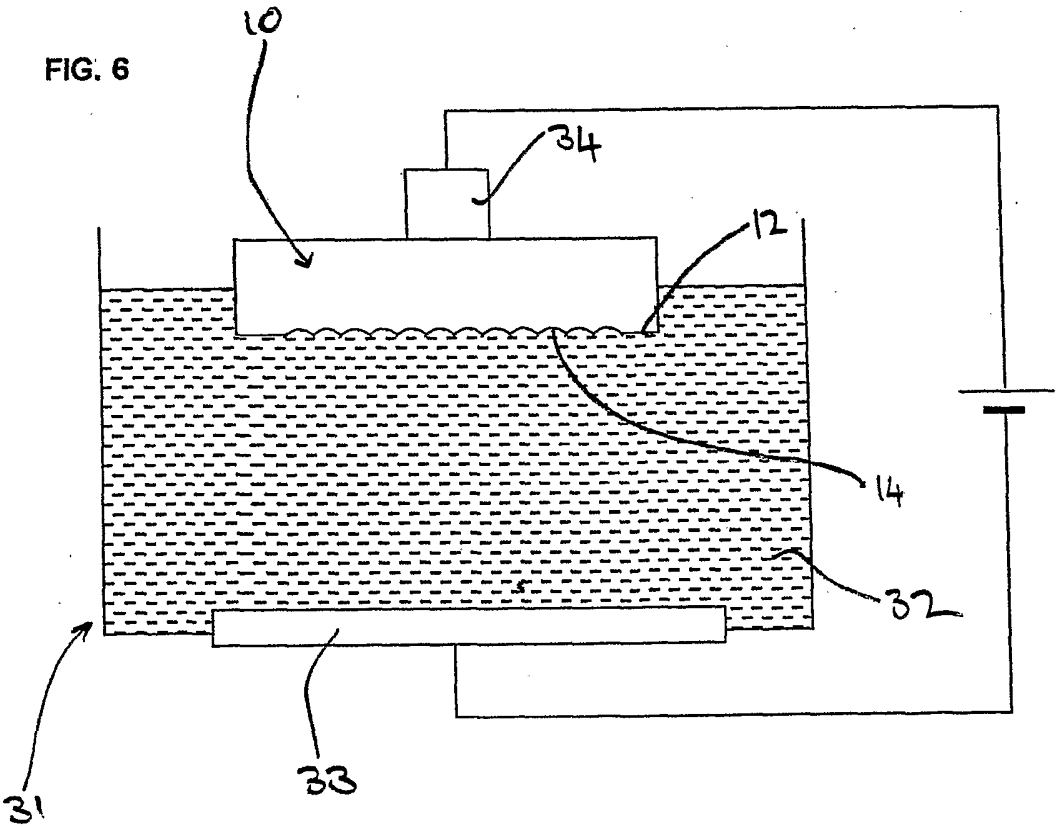

FIG. 7a

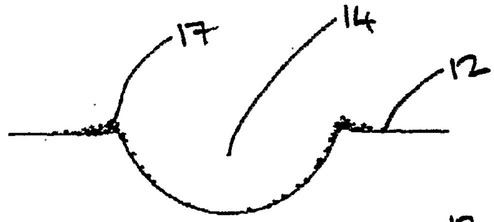

FIG. 7b

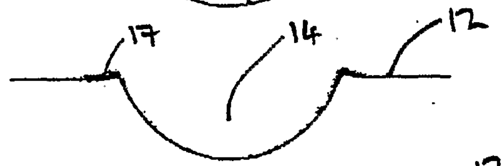

FIG. 7c

FIG. 7d

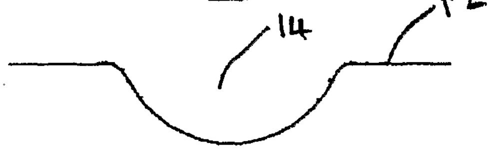

FIG. 8

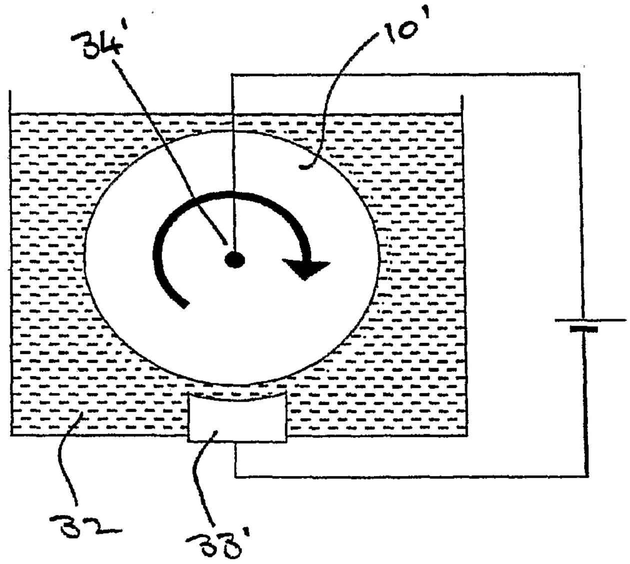

FIG. 9a

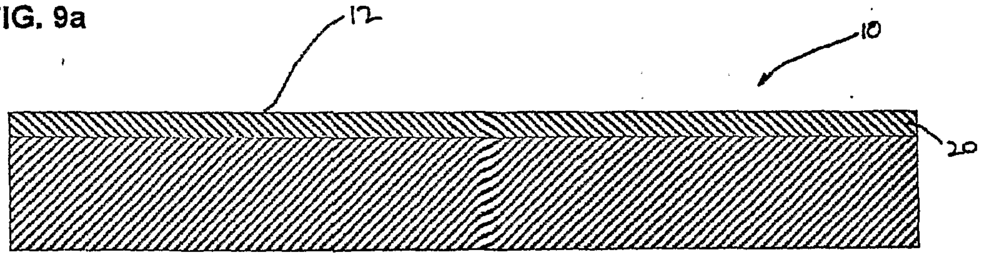

FIG. 9b

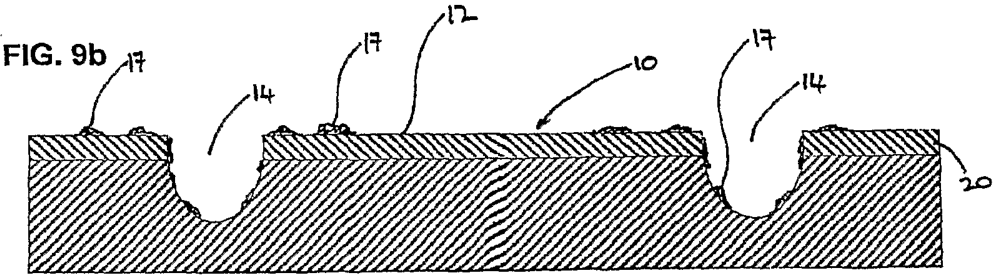

FIG. 9c

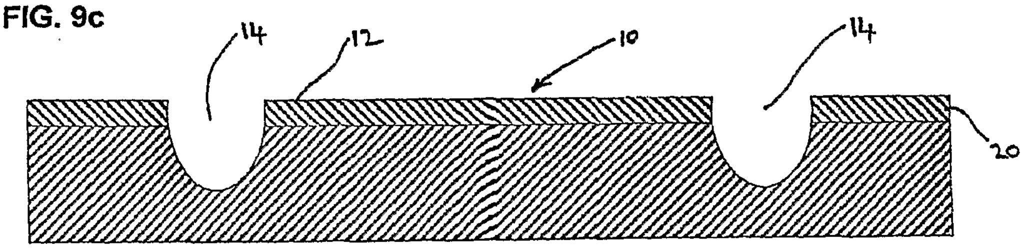

FIG. 9d

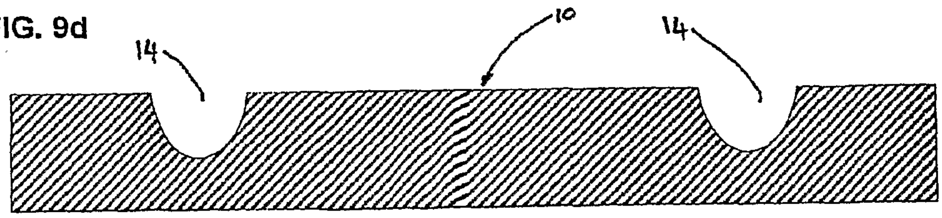

FIG. 10a

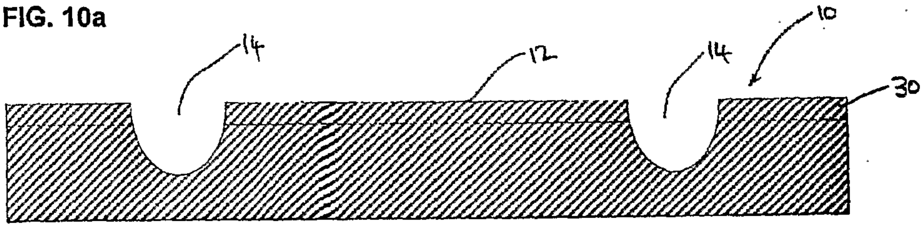

FIG. 10b