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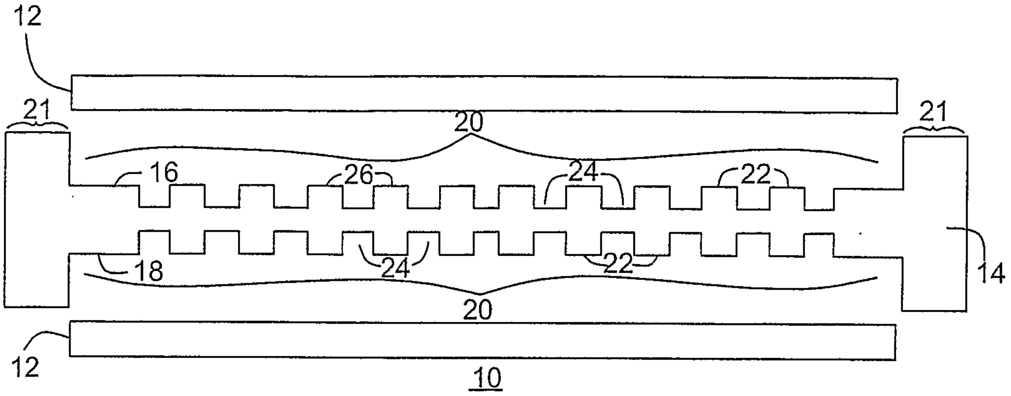

(57) Abstract: Separation elements (10) and methods for making separation elements (10) include permeable polymeric membranes (12) which are thermally bonded to polymeric structural members (14). The separation elements may be used to purify, segregate, and/or concentrate a variety of fluids and/or fluid components.

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SEPARATION ELEMENTS AND METHODS OF MAKING SEPARATION ELEMENTS

This application claims the benefits of priority based on United States Provisional Application no. 60/618,144 which was filed on October 14, 2004, and is incorporated by reference.

DISCLOSURE OF THE INVENTION

The present invention relates to separation elements and methods of making separation elements and in particular to separation elements including permeable polymeric membranes thermally bonded to polymeric structural members. The separation elements may be used to purify, segregate, and/or concentrate a variety of fluids and/or fluid components.

In accordance with an aspect of the invention, a separation element comprises a polymeric structural member and a permeable polymeric membrane. The polymeric structural member includes at least one polymeric component having a softening temperature and an active region which includes a plurality of protrusions, each protrusion including at least one bonding site. The permeable polymeric membrane has a pore structure which permits fluid to flow through the membrane. The permeable polymeric membrane also has a softening temperature which is higher than the softening temperature of the polymeric component of the structural member. The permeable polymeric membrane is thermally bonded to the polymeric structural member at the bonding sites, the polymeric component at the bonding sites being resolidified in contact with the permeable polymeric membrane without substantially collapsing the pore structure of the permeable polymeric membrane in the active region.

In accordance with another aspect of the invention, a method of making a separation element comprises registering a permeable polymeric membrane and a polymeric structural member. The permeable polymeric membrane has a pore structure which permits fluid to flow through the membrane and overlies an active region of the polymeric structural member which includes a plurality of protrusions, each protrusion including at least one bonding site. The method also comprises heating the bonding sites of the polymeric structural member to a temperature at or above the softening temperature of at least one polymeric component of the structural member, including softening the polymeric component at the bonding sites. The method further comprises applying pressure to the permeable polymeric membrane and the polymeric structural member, including resolidifying the softened polymeric component at the bonding sites in contact with the permeable polymeric membrane, to thermally bond the permeable polymeric membrane to the polymeric structural member without substantially collapsing the pore structure of the membrane in the active region.

Separation elements and methods of making separation elements in accordance with the present invention offer many advantages. For example, the present separation elements provide permeable polymeric membranes securely bonded to polymeric structural members. Polymeric structural members provide structural integrity to the separation elements and may constitute a substantial structure of any device formed by the separation elements, including pressure containment means. The polymeric structural members also provide feed and/or drainage passages having low resistance to flow. The secure bond between the permeable membranes and the structural members enables the membranes to withstand forces that would otherwise tear them apart, e.g., forces encountered during cross-flow fluid treatment and backwashing operations. The secure bond also enables the membranes to withstand forces that would otherwise cause them to billow into and occlude adjacent channels. The bonding sites on the protrusions in the active region of the polymeric structural member are exposed to a heat source that is hotter than the softening temperature of at least one polymeric component of the structural member. The softened bonding sites are then resolidified in contact with the permeable polymeric membrane. This results in a highly secure bond in the active region of the polymeric structural member. Yet, the thermal bond, while secure, does not result in a substantial collapse of the pore structure of the membrane, which allows the membrane to remain highly permeable in the active region. Further, separation elements and methods embodying the invention avoid the introduction of contaminants into the fluid streams passing through them. For example, there are no bonding agents, such as adhesives or solvents, which may leach contaminants into the fluid streams.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1 is an exploded end view of a separation element.

Figure 2 is a bottom view of the separation element of Figure 1.

Figure 3 is a cross-sectional view of the thermally bonded separation element of Figure 1.

Figures 4a and 4b are scanning electron micrographs of a thermally bonded permeable membrane.

Figure 5 is an exploded end view of another separation element.

Figure 6 is an exploded cross-sectional view of a separation module.

DESCRIPTION OF EMBODIMENTS

While many different separation elements may embody the invention, in one example, illustrated in Figure 1, a separation element 10 may comprise at least one permeable polymeric membrane 12, e.g., first and second permeable polymeric membranes, thermally bonded to a polymeric structural member 14. The polymeric structural member 14 may be any structure having sufficient structural integrity to support the permeable membrane 12. The structural member may be flexible, semi-flexible, e.g., slightly bendable, or rigid. In the illustrated embodiment, the polymeric structural member 14 may comprise a plate-like member having at least one side, e.g., first 16 and second 18 sides, including one or more active regions 20 having a plurality of protrusions 22. Each protrusion 22 may include at least one bonding site 26 and the protrusions 22 may define a plurality of regular or irregular fluid passageways. For example, the protrusions may comprise ridges, e.g., long narrow elevations, and valleys, e.g., grooves, between adjacent ridges which may comprise fluid flow channels 24. Fluid to be treated by the separation element 10 may be directed through the permeable polymeric membranes 12 toward the polymeric structural member 14, with permeate being received by the passageways in the polymeric structural member 14, e.g., by the channels 24. Alternatively, fluid to be treated by the separation element 10 may be directed along the passageways in the polymeric structural member 14, e.g., along the channels 24, with permeate passing through the permeable polymeric membranes 12 away from the polymeric structural member 14. The active region 20 of the polymeric structural member 14 may comprise a region which receives permeate from the membranes 12 or which directs fluid to be treated through the membranes 12.

In many embodiments, the permeable polymeric membranes 12 may be thermally bonded to the polymeric structural member 14 at bonding sites 26 on the protrusions 22 in the active region 20. For example, a first permeable polymeric membrane 12 may be thermally bonded at the bonding sites 26 on the protrusions on the first side 16 of the structural member and a second permeable polymeric membrane 12 may be thermally bonded at the bonding sites 26 on the protrusions 22 on the second side 18 of the structural member 14. The bonding sites 26 may include points or regions of contact between the polymeric structural member 14 and the permeable polymeric membranes 12. The active region 20 comprises many or all of the bonding sites 26.

The polymeric structural member 14 comprises at least one polymeric component having a softening temperature, and each permeable polymeric membrane 12 comprises at least one polymeric component having a softening temperature higher than the softening temperature of the polymeric component of the structural member. For example, the polymeric structural member may comprise only one principal polymeric component, and the sole polymeric component of the structural member may have a softening temperature which is lower than the softening temperature of one or more, e.g., all, of the polymeric components of the permeable membrane. Alternatively, the polymeric structural member may comprise two or more polymeric components, one or more, e.g., all, of which have softening temperatures lower than the softening temperature of one or more, e.g., all of the polymeric components of the permeable membrane. In some embodiments, the polymeric structural member may include one or more polymeric components which may having softening temperatures equal to or higher than the softening temperatures of the permeable polymeric membrane, but at least one of the polymeric components of the structural member has a softening temperature which is lower than the lowest softening temperature of the polymeric components of the permeable membrane. The softening temperature may be described as the temperature sufficient to at least partially soften a polymer so that the polymer can plastically deform or viscously flow. The difference between the softening temperature of at least one polymeric component of the structural member and the permeable polymeric membranes is preferably enough to facilitate exposing both the polymeric structural member and the membranes to a heat source and softening at least one polymeric material at the bonding sites of the structural member without softening the membranes. For example, for some embodiments, there may be a difference of up to about 10°C or more between the softening temperatures of the polymeric components of the polymeric structural member and the permeable membranes.

The polymeric structural member may comprise a variety of polymeric materials including one or more polymers or co-polymers. Exemplary polymeric materials include, but are not limited to, polypropylene, polyester, polystyrene, polycarbonate, polyethylene, polysulfone, polyethersulfone, polyimide, polyetherimide, polyamide, polyvinylchloride (PVC), perfluoroalkoxy (PFA), fluorinated ethylene propylene (FEP), polyvinylidene fluoride (PVDF), poly-ether-ether ketone (PEEK), polyacrylonitrile (PAN), and polytetrafluoroethylene (PTFE). The polymeric structural member may also include non-polymeric components as well. For example, the polymeric structural member may include one or more additives or fillers, such as fiberglass or talc. The polymeric structural members may be formed in any of numerous processes, including any injection-molding or machining process. In some embodiments, a preferred polymeric structural member material may comprise an injection-molded polysulfone member.

The polymeric structural member 14 may have any of a multitude of geometries and configurations. While the illustrated embodiment may include a substantially planar rectangular structural member 14, e.g., a flat plate, the structural member may have a variety of other geometrical configurations, e.g., curved, circular, polygonal, or cylindrical. The polymeric structural member may include the active region 20, which includes protrusions 22 that define a plurality of fluid passageways, and a peripheral region 21 spaced from the active region 20. The peripheral region may comprise one or more edge regions of the structural member and may, in some embodiments, comprise a perimeter of the structural member surrounding the active region. In many embodiments, the peripheral region comprises the same material, e.g., the same polymeric component or components, as the active region of the structural member. In many embodiments, the peripheral region is substantially impermeable, e.g., non-porous, but may include one or more fluid conduits, for example, one or more fluid inlet or outlet ports. The polymeric structural member may have a height, i.e., the distance from one surface to an opposite surface of the member, which is constant or varies in different regions of the member, e.g., in the peripheral and the active regions. In some embodiments, the height of the structural member in the active region may be from about 0.0625 inch or less up to about 0.5 inch or more, for example, in some embodiments the height of the active region may be about 0.1875 inch. The peripheral region may have a height greater than, equal to or even less than the height of the active region 20. In many embodiments, the height of the peripheral region is greater than the height of the active region. For example, in some embodiments the height of the peripheral region may extend beyond the height of the active region by from about 0.01 inch or less up to about 0.12 inch or more, e.g., from about 0.015 inch or less up to about 0.115 inch or more.

In many embodiments, the structural member 14 includes a plurality of protrusions 22 which may define a plurality of passageways, e.g., channels 24, on or within the surface of the structural member 14. The plurality of protrusions 22 may take any of numerous regular or irregular forms, for example, as ribs, lands, ridges, and/or knobs, and may be formed by a variety of processes, such as by molding or machining. The passageways may have a variety of configurations, including but not limited to channels having generally V-shaped configurations, generally U-shaped configurations, semi-circular configurations or generally rectangular configurations. In the illustrated embodiment, the protrusions 22 may comprise a plurality of elongated ridges and the passages may comprise a plurality of parallel elongated channels 24 extending from one edge of the structural member 14 to an opposite edge. However, the protrusions and passages may have other configurations; for example, some protrusions and passages may not be parallel to others and/or some protrusions and passages may extend from other than one edge to an opposite edge of the structural member. In some embodiments (not shown), the passageways between adjacent ridges may comprise openings, e.g., holes or slots, extending through the thickness of the structural member, such that fluid in the passages may pass from a first side of the structural member to a second side of the structural member.

The passages may define any of a multitude of flow paths across and/or through the polymeric structural element. The passages may comprise feed channels from which fluid to be treated passes to the permeable polymeric membranes or permeate channels which receive permeate from the membranes. In many embodiments, the passageways may be substantially unobstructed, e.g., substantially free of structure. Unobstructed passages may be advantageous in many embodiments because the absence of any structure in the passage reduces the resistance to flow and thus reduces the pressure drop across the separation element.

The permeable polymeric membranes may comprise any of numerous separation media, and the first and second membranes may be identical or different. In many embodiments, the first and second permeable membranes are identical. The membranes preferably have any pore structure which permits fluid to flow through the membrane. The pore structure may be any arrangement of pores, passages or other openings which extend through the membrane or interconnect with one another within the membrane to permit fluid flow between opposite surfaces of the membrane and which effect the separation of one or more components from the fluid. The pore structure may be defined by a variety of removal ratings. Membranes may include microporous membranes (e.g., membranes generally having removal ratings of from about 0.1 μm to about 100 μm or more), ultrafiltration membranes (e.g., membranes generally having removal ratings of less than about 0.1 μm), nanofiltration membranes (e.g., membranes generally having removal ratings of from about 10 Å to about 100 Å), and reverse osmosis membranes (e.g., membranes generally having removal ratings of less than about 10 Å). Exemplary separation media include porous, permeable or semipermeable polymeric films or woven or non-woven sheets of polymeric fibers. For many embodiments, the permeable polymeric membranes may comprise a porous or permeable polymeric film.

The membranes may be prepared from any suitable polymeric material including any of the polymeric materials identified above, as well as cellulose, and/or cellulose derivatives, and may be formed in any suitable process, including any casting, extruding, expanding, weaving, fiber lay-down or fiber weaving process. The permeable polymeric membranes may comprise one or more polymeric components forming the structural matrix of the membrane, and may include additional non-polymeric components as well. Further, the membranes may be treated in any of numerous ways to impart one or more of various characteristics to the membranes. For example, the membranes may be surface treated to affect the wettability of the membrane or to affect the capture characteristics of the membrane.

The permeable polymeric membranes 12 may comprise supported or unsupported membranes. An unsupported membrane may include a separation region which has the pore structure of the membrane. A supported membrane may include a separation region and a support region on and/or within which the separation region may be supported. The separation region may include the pore structure of the membrane and the support region may comprise a fibrous woven or nonwoven web. In embodiments including an unsupported or a supported membrane, the polymeric structural member may be thermally bonded to the separation region, e.g., to the surface of or within the pore structure. In embodiments including a supported membrane, the separation region and the support region may comprise identical or different materials. For many embodiments, all of the polymeric components forming the structural matrix of the membrane 12, i.e. the separation region, may have softening temperatures which are higher than the softening temperature of at least one polymeric component at the bonding sites 26 of the polymeric structural member 14. Consequently, at least one polymeric component at the bonding sites 26 may be softened without softening the separation region of the permeable membrane 12. Since the separation region of the permeable membrane is not softened, the thermally bonded membrane may not include any resolidified polymeric components from the separation region. The softening temperature of the polymeric component of the support region of the membrane may be greater than, equal to, or even less than the softening temperature of the polymeric component of the separation region.

Many different permeable polymeric membranes and polymeric structural members may be paired with one another to facilitate softening at least one polymeric component of the structural member without softening the permeable membrane, i.e., the separation region. Examples of some of the more preferred pairs include:

1) a cast, unsupported polyethersulfone membrane and a polysulfone structural member;

2) a cast, unsupported polyethersulfone membrane and a polypropylene structural member; and

3) a cast, unsupported polyethersulfone membrane and a polyetherimide structural member.

The permeable polymeric membranes 12 are thermally bonded to the bonding sites 26 in the active region 20 of the polymeric structural member 14. The bonding sites 26 may be configured in a variety of ways. For example, the bonding sites 26 may comprise a plurality of discrete points or areas on the protrusions 22 on one or both surfaces of the polymeric structural member 14. In the illustrated embodiment, the bonding sites 26 comprise long, thin regions extending along the length of each protrusion 22 at the outer surface, e.g., along a crest of a ridge. However, in some embodiments, the bonding sites may extend for less than the entire length of the protrusion and may comprise discrete points or areas spaced along the length of the protrusion.

As best seen in Figure 3, one permeable polymeric membrane 12 may be thermally bonded to the bonding sites 26 along the protrusions 22 on the first side 16 of the polymeric structural member 14 and the other permeable membrane 12 may be thermally bonded to the bonding sites 26 along the protrusions 22 on the second side 18 of the polymeric structural member 14. The polymeric material at the bonding sites is resolidified in contact with the permeable membranes, e.g., at an interface region 30 between the separation region of the permeable membrane 12 and each bonding site 26, to thermally bond the permeable polymeric membrane 12, i.e., the separation region, to the polymeric structural member 14. The interface region 30 may comprise a mass of resolidified polymeric material, e.g., from the bonding site, in contact with a surface 32 of the permeable membrane 12, e.g., the separation region and the pore structure, and/or the interface 30 region may comprise a mass of resolidified polymeric material extending into the separation region and the pore structure of the membrane 12 beyond the surface 32, e.g., into the interstices of the membrane 12 slightly beyond the surface 32. For example, softened polymeric material from the bonding site may move through a support region of the permeable membrane, into contact with the surface and/or the interstices of the separation region and the pore structure and resolidify. In some embodiments, the interface 30 region may include some resolidified polymeric material from other than the bonding site e.g., from the support region of the permeable membrane. However, the interface region 30 preferably does not include any resolidified polymeric membrane matrix material, e.g. from the separation region of the permeable membrane. Although the polymeric material at the bonding sites is resolidified in contact with the permeable membrane 12, the pore structure of the permeable membrane may be occluded only at the interface region 30. In most embodiments, the pore structure of the permeable membrane 12 in the region 34 beyond the interface region 30, i.e., between the interface region and the opposite surface of the membrane 12, is neither occluded nor collapsed. In some embodiments, the pore structure of the permeable membrane 12 in the region 36 above the interface region may be modified, e.g., slightly compressed, but the region 36 remains largely permeable. Thus, the thermally bonded permeable polymeric membranes 12 remain highly permeable in the active region 20. For example, as illustrated by the arrows indicating flow in Figure 3, fluid may flow freely through the membrane 12, e.g., from one surface to an opposite surface, in areas 34 spaced from the bonding sites 26. In other areas 36 adjacent the bonding sites 26, fluid may flow freely through the surface of the permeable polymeric membrane 12 and laterally through the membrane 12 away from the bonding sites 26.

The scanning electron micrographs (SEM) in Figures 4a and 4b show the pore structure of an unsupported polyethersulfone membrane which has been thermally bonded to a polysulfone structural member in general accordance with the present invention. In Figure 4a, the pore structure of the membrane in a region above a fluid passageway is shown and, comparatively, in Figure 4b, the pore structure of the membrane in a region above the interface region is shown. As can be clearly seen, although the pore structure of the membrane above the interface region (Figure 4b) may be slightly altered, e.g., slightly compressed, the pore structure is not substantially less porous than the pore structure above a fluid passageway (Figure 4a), and the pore structure is not substantially collapsed in either region.

In some embodiments, the separation element may include additional layers. For example, in the embodiment illustrated in Figure 5, at least one intermediate layer 38 may be disposed between the permeable polymeric membrane 12 and the polymeric structural member 14. Although the embodiment illustrated in Figure 5 includes only a single permeable polymeric membrane 12 and a single intermediate layer 38 on only one side of the polymeric structural member 14, the separation element 10 may include multiple intermediate layers on one side of the polymeric structural member and/or a second permeable polymeric membrane, with or without a second intermediate layer on the other side of the structural member. The intermediate layer 38 may have a variety of functions and configurations. For example, for many embodiments, the intermediate layer 38 may comprise a reinforcing layer, a fluid distribution layer, and/or a cushioning layer and may be in the form of a mass of fibers, woven or nonwoven fibrous sheets or meshes. Any of a variety of materials may be utilized, including polymeric and fiberglass materials. The polymeric component or components comprising the intermediate layer may have a variety of softening temperatures, for example, softening temperatures greater than, equal to or even less than the softening temperature of the polymeric structural member. In some embodiments, the intermediate layer may comprise a polyetheretherketone mesh.

While many different methods for making a separation element may embody the present invention, one exemplary method may comprise registering at least one permeable polymeric membrane and a polymeric structural member. For example, the permeable polymeric membrane and polymeric structural member are preferably registered, e.g., aligned, so that the permeable polymeric membrane overlies an active region of the structural member. In many embodiments, registering the permeable polymeric membrane and the structural member may include positioning the permeable polymeric membrane adjacent to a surface of the polymeric structural member in the active region. In some embodiments, registering the permeable polymeric membrane may include registering two permeable polymeric membranes with opposite sides of a structural member, e.g., simultaneously or sequentially. The permeable polymeric membrane may be placed in direct contact with the structural member or may be slightly spaced from the member. In other embodiments, registering the permeable polymeric membrane and polymeric structural member may include positioning the permeable polymeric membrane adjacent to a surface of at least one intermediate layer, the intermediate layer being positioned adjacent to a surface of the structural member in the active region.

The exemplary method may also comprise heating at least the polymeric structural member. For example, at least the bonding sites in the active region of the polymeric structural member may be heated. Any suitable heating arrangement may be used, including, but not limited to, electrical resistance, induction, microwave, radio frequency, sonic, convection, and/or radiant heaters. For example, in many embodiments, the polymeric structural member may be heated by positioning a heated platen in proximity to, e.g., on or near, the surface of the polymeric structural member to which the permeable polymeric membrane will be bonded. The heating arrangement may be applied to the structural member before the permeable polymeric membrane is registered with the member. However, for many embodiments, the heating arrangement may be applied to the polymeric structural member after the permeable polymeric membrane and any intermediate layer are registered with the structural member. In many embodiments, a protective layer such as a non-stick polytetrafluoroethylene (PTFE) sheet may be located between the heated platen and the structural member, e.g., between the heated platen and the permeable membrane. In some embodiments, a non-stick protective layer may comprise a PTFE coating on the platen surface. Energy from the heating arrangement may pass through the permeable membrane and any intervening layers, e.g., any protective layer and/or intermediate layer, to the polymeric structural member. Heating the structural member after the membrane and any intermediate layer are registered has several advantages. For example, the bonding sites don't cool while the permeable membrane and any intermediate layer are being registered with the polymeric structural member.

The heating arrangement may be arranged to heat at least the bonding sites of the polymeric structural member to a temperature which is at or above the softening temperature of at least one polymeric component or the structural member. In some embodiments, bonding sites in active regions on both sides of the structural member may be heated, e.g., heated simultaneously or sequentially. Consequently, at least one polymeric component of the structural member at the bonding sites may become at least soft, e.g. plastically deformable, and may even be capable of flowing, e.g. viscously flowing. After bonding the permeable membrane and any intermediate layer to the polymeric structural member, the polymeric structural member preferably retains much of its structural integrity and form. The heating arrangement preferably does not heat the polymeric structural member to the extent that the structural member and in particular the protrusions grossly deform, for example, where the protrusions lose their prior shape. Further, where the polymeric structural member is heated after the permeable polymeric membrane and any intermediate layer are registered with the structural member, the heating arrangement may be arranged to heat the structural member through the polymeric membrane and the intermediate layers without collapsing the pore structure of the membrane. For example, the heating arrangement may be arranged to heat the bonding sites on the protrusions of the structural member to a temperature which is at or above the softening temperature of at least one or more than one or all of the polymeric components at the bonding sites and to heat the permeable polymeric membranes to a temperature which is below the softening temperatures of all of the polymeric components of permeable membrane, i.e. the polymeric components forming the matrix of the separation region. The heating arrangement may heat any intermediate layer or any support region of the permeable membrane to a temperature below, equal to, or even higher than the softening temperature of any polymeric component of the intermediate layer. In many embodiments, all of the polymeric components of the structural member at the bonding sites are at least softened and the polymeric components of any intermediate layer or support region may or may not be softened, but the matrix, e.g., the separation region of the permeable polymeric membranes, is not softened. The amount of energy supplied by the heating arrangement, e.g. its temperature; the amount of time that the heating arrangement heats the polymeric structural member, e.g. directly or through the permeable membrane and any intermediate layer; and the proximity of the heating arrangement to the structural member, the permeable membrane, and any intermediate layer to appropriately heat the bonding sites, are bonding process parameters which depend on factors such as the structure, composition, and characteristics of the permeable membrane, the structural member, and any intermediate layer, including, for example, the softening temperatures, the thicknesses and the insulative qualities of one or more of these elements. These parameters may be determined empirically for each combination of permeable membrane, structural member and any intermediate layer. As a general guide, in most embodiments, the heating arrangement may be heated to at least the softening temperature of at least one polymeric component of the structural member, e.g., the highest softening temperature of the polymeric components. In some embodiments, due to the insulative quality of any intervening layers, e.g., any protective layer and/or intermediate layer present between the heating arrangement and the bonding sites, the heating arrangement may be heated to temperatures greater than the softening temperature of a polymeric component of the structural member. In some embodiments, due to the presence of the insulating intervening layers, the heating arrangement may be heated to as high as or higher than the softening temperature of the polymeric components of the separation region of the permeable membrane without softening the permeable membrane.

The exemplary method may also comprise applying pressure to the structural member and/or the permeable polymeric membrane to press the heated bonding sites of the structural member against the permeable membrane, e.g., the separation region and the pore structure of the permeable membrane. In embodiments including permeable membranes on opposite sides of the structural member, the heated bonding sites on both sides of the structural member may be pressed against the adjacent permeable membrane. The pressure may be applied in the vicinity of the bonding sites by various mechanisms, including, for example, rollers; spring-biased, pneumatic, screw-driven or hydraulic plates; or weights. The pressure may be applied directly to the permeable membrane and/or the structural member, with or without any intervening layer or indirectly. For example, a protective layer, such as a non-stick PTFE sheet, may be located between the permeable membrane and the pressure mechanism. The pressure may be applied while the heating arrangement heats the bonding sites of the structural member and/or after the heating arrangement heats the bonding sites of the structural member. In some embodiments, the pressure may be applied, at least in part, by the heating arrangement. For example, a heated platen may soften the bonding sites of the structural member and simultaneously press the permeable membrane against the structural member, which may rest on a heated or unheated base.

When the permeable membrane is pressed against the heated bonding sites in the active region of the polymeric structural member, with or without any intervening layer, the softened polymeric component of each bonding site is pressed into contact with at least the surface of the permeable membrane, i.e., the surface of the separation region, at an interface region. For example, the softened polymeric component of the bonding sites may plastically deform, or even flow, through any intermediate layer and through any support region into contact with the surface of the separation region of the permeable membrane, at the interface regions. In some embodiments, one or more interface regions may extend into the permeable membrane, i.e., into the interstices of the support region and even into the separation region. The softened polymeric component of the bonding site may penetrate beyond the surface of the separation region and into the membrane matrix pore structure. For example, the polymeric component of the bonding site may penetrate into less than about 50% or less than about 25% or less than about 10% or less than about 5% of the thickness of the separation region of the permeable membrane. However, in some embodiments, the polymeric component of the bonding site may not appreciably penetrate into the separation region of the permeable membrane at all. In many embodiments, the softened polymeric component may also plastically deform in a lateral direction, e.g., the polymeric component may spread outwardly away from the bonding site. Less penetration into the thickness of the permeable membrane and less lateral spread are both preferred because they result in less occlusion of the pore structure and greater permeability of the membrane outside of the interface region.

To further enhance the permeability of the membrane above the interface region, the permeable membrane is pressed against the heated bonding sites in the active region of the structural member without significantly crushing or collapsing the pore structure of the membrane above the interface regions. Although the pore structure above the interface regions may, or may not, be altered by the application of pressure, as well as by heat, the membrane remains permeable above the interface regions because the pore structure is not significantly crushed or collapsed. The amount of pressure and the amount of time pressure is applied to appropriately press the permeable membrane and the structural member together are bonding process parameters which depend on factors such as the structure, composition, and characteristics of the permeable membrane, the polymeric structural member, and any intermediate layer, including, for example, the compressive yield strength of the permeable membrane. These parameters may be determined empirically for each combination of permeable membrane, structural member, and any intermediate layer.

The exemplary method may also comprise resolidifying the softened polymeric component of the bonding sites in the interface regions, thereby thermally bonding the permeable membrane, e.g., the separation region of the permeable membrane, to the structural member, with or without any intermediate layer. The softened polymeric component of the bonding sites may be resolidified by cooling the softened polymeric component in contact with, e.g., on and/or within, the separation region of the permeable membrane. For example, the heating arrangement may be removed or it may cease supplying heating energy, allowing the temperature of the polymeric structural member to fall below the softening temperature of the polymeric material and return to ambient temperature. Alternatively, the combination of the permeable membrane, the structural member, and any intermediate layer may be actively cooled, for example, by directing a cooling fluid through the base on which the structural member rests. As the softened polymeric material at the bonding sites in the interface regions cools and resolidifies, the permeable membrane, the structural member, and any intermediate layer may continue to be pressed against one another to maintain contact between the permeable membrane and the bonding sites of the structural member and thereby enhance the thermal bond.

Methods for making separation elements, and the separation elements themselves, provide a permeable membrane which is thermally bonded to a polymeric structural member, and, in the active region, the membrane remains highly permeable while being securely fixed to the structural member. The membrane may be bonded to the structural member without crushing or collapsing the pore structure above the interface region at each bonding site. This increases fluid flow in the active region through the membrane in either direction because more of the membrane is available for fluid flow. For example, fluid may enter the surface of the membrane above the interface regions at the bonding sites and flow edgewise or laterally through the uncollapsed pore structure, exiting the opposite surface of the membrane at the unoccluded portions of the membrane between the interface regions. Yet, the highly permeable membrane is securely fixed to the polymeric structural member. Because the separation region of the permeable membrane is thermally bonded to the structural member, a highly secure bond is achieved. Further, in embodiments where all of the polymeric material at the bonding sites is softened, i.e., when the polymeric structural member is heated to a temperature higher than the softening temperatures of all of the polymeric components of the member and then resolidified in contact with the permeable membrane, e.g., the separation region of the membrane, all of the bonding sites, and the entire area of each bonding site, are available to participate in the thermal bond. This results in a tight, secure thermal bond between the permeable membrane and the structural member. The secure bond may prevent the permeable membrane from billowing into adjacent fluid flow channels. These secure thermal bonds may also, for example, be capable of withstanding repeated reverse flows, i.e., flow from the structural member through the permeable membrane, of liquid and/or gas. For example, the separation element may be repeatedly cleaned by directing liquid and/or gas in a reverse direction through the permeable membrane or repeatedly subjected to Starling flow, without ripping the permeable membrane away from the structural member.

While methods for making separation elements and the separation elements themselves may have a highly permeable membrane in the active region of the polymeric structural member, outside of the active region the permeable membrane may be bonded to the structural member very differently. For example, in the peripheral region of the structural member, the membrane and the structural member may be bonded to one another and/or other structural elements in a manner which seals the separation element in the peripheral region. In some embodiments, sufficient heat and/or pressure may be applied to the membrane and/or the structural member outside of the active region, e.g., in the peripheral region, to completely crush or collapse the pore structure of the membrane and thereby seal the periphery. In other embodiments, sealants or adhesives may be applied to the membrane and the polymeric structural member outside of the active region to completely occlude the pore structure of the membrane. However, within the active region the permeable membrane remains highly permeable and securely thermally bonded to the polymeric structural member.

EXAMPLE

A SUPOR™ unsupported polyethersulfone membrane is thermally bonded to a polysulfone structural member using a heated platen. The polyethersulfone membrane is registered atop an active region of a polysulfone structural member including a plurality of ridges defining channels between them, and a 3 mil thick sheet of PTFE is positioned between the polyethersulfone membrane and the heated platen. The polysulfone structural member rests on an unheated base. The platen is heated to a temperature of 435 °F and applied to the stack of PTFE sheet, membrane, and structural member. Pressure of about 237 psi is applied to the stack for approximately 75 seconds to soften the bonding sites of the structural member and to allow softened polysulfone at the bonding sites to contact the polyethersulfone membrane, i.e. the separation region, without significantly collapsing the pore structure of the polyethersulfone membrane in the active region. A metal plate is placed over the stack, after the platen is removed, to facilitate cooling of the heated layers under pressure. Upon cooling, the softened polysulfone at the bonding sites resolidifies in the interface regions, providing a highly permeable polyethersulfone membrane in the active region which is securely fixed to the bonding sites of the polysulfone structural member.

In some embodiments, one or more separation elements may be combined with a feed inlet arrangement and a permeate outlet arrangement to form a separation module. Fluid to be treated by the separation element(s) may enter the module through the feed inlet arrangement and flow to one or more separation elements. Feed fluid may flow along feed passages and fluid passing from the feed passages through the permeable polymeric membrane, e.g., permeate, may flow along permeate passages to the permeate outlet arrangement to be removed from the module. In some embodiments the module may be adapted for cross-flow separation and a portion of the fluid, e.g., retentate, may exit the module through a retentate outlet arrangement without passing through the permeable polymeric membrane.

The separation module may be variously configured in a wide variety of structures and geometries. One of a myriad of examples of a separation module 100 including a plurality of stacked separation elements 10 sealed to one another is illustrated in Figure 6. While the illustrated separation module 100 comprises rectangular separation elements 10, the separation module 100 may have a variety of other geometric configurations, e.g., circular separation elements. The separation module 100 may also include any suitable number of separation elements 10, for example two, three, four, five, or even more, e.g., up to 10 or more or 20 or more, which may be stacked and sealed between opposite end plates 121.

Separation modules embodying the invention may include a multitude of flow paths, e.g., feed, permeate, and retentate flow paths, through the module. The flow paths may have a variety of configurations in order to efficiently distribute fluid throughout the module, for example, to efficiently distribute feed fluid to the separation elements and remove permeate and retentate from the separation elements. The separation module may introduce feed fluid to, remove permeate from, and remove retentate from any suitable location on the module. Many different sealing arrangements may be used to seal appropriate fluid passages and inlet and outlet arrangements from one another. For example, grommets, gaskets, sealants, adhesives or heat seals may isolate the various passages from one another.

The separation module may include a feed inlet arrangement having a myriad of configurations. For example, the feed inlet arrangement may introduce fluid at an end region of the module or at a top or bottom portion of the module. The feed inlet arrangement may direct feed fluid to flow along any suitable path, e.g., along a feed passage having any suitable configuration, from the feed inlet arrangement to the separation elements. In the illustrated embodiment, an exemplary feed inlet arrangement 120 may comprise one or more feed ports (not shown) in one or both end plates 121 and a feed manifold 122 communicating with the feed port(s) and located at an end region of the stack of separation elements 10, allowing the introduction of feed fluid at a lengthwise end of the module 100. The feed manifold 122 distributes feed fluid along feed passages 124 comprising open spaces, meshes or channeled plates present between the separation elements 10. In the active region 20 of each separation element 10, permeate passes through the permeable polymeric membranes 12 facing the feed passages 124 to permeate passages comprising permeate channels 126, e.g., valleys between adjacent ridges, in the structural members 14. Alternatively, the structural members of the separation elements may define the feed passages and the permeate passages may comprise open spaces, meshes or channeled plates between adjacent membranes. Since the permeable membranes are securely thermally bonded to the rigid structural members, many embodiments have open spaces between adjacent membranes rather than structural features, such as meshes or channeled plates, which hold the membranes against the polymeric structural members and prevent the permeable membranes from billowing and/or the structural members from flexing. Advantageously, the absence of these structural features provides fluid flow passages adjacent the membranes, e.g., feed or permeate passages, having a lower resistance to fluid flow and uniform shear on the membrane surfaces.

The permeate outlet arrangement may have any of a multitude of configurations. The permeate outlet arrangement may comprise permeate conduits, one or more holes or other passages extending through the stack of separation elements and communicating with the permeate passages. The permeate outlet arrangement may remove permeate from the separation elements outside of the active region and spaced from the feed inlet arrangement. For example, in some embodiments, the permeate outlet arrangement may comprise a manifold located at an end region of the separation module. The permeate outlet arrangement may remove permeate from the top or bottom of the separation module or at any intermediate position. In the illustrated embodiment, an exemplary permeate outlet arrangement 130 may comprise one or more permeate ports 132 and permeate cutouts 131 in opposite end regions of each separation element 10 which communicate with the permeate ports 132. The cutouts 131, in turn communicate with the permeate passages 126 in the structural members 14, allowing permeate to exit the module 100. The permeable membrane 12 of each separation element 10 may overlie the permeate cutouts 131, isolating the permeate cutouts 131 from the feed passages 124. In some embodiments, the protrusions 22 may extend above and across the permeate cutouts 131 thereby supporting and providing bonding of the permeable membrane 12 to the structural member 14 over the permeate cutouts 131.

In embodiments adapted for cross-flow filtration, a retentate outlet arrangement may remove retentate from the separation module. The retentate outlet arrangement may have any of numerous configurations. For example, in the illustrated embodiment, the retentate outlet arrangement 140 may comprise one or more retentate ports (not shown) in one or both end plates 121 and a retentate manifold 142 located at an end region of the module, opposite the feed inlet arrangement 120 which communicates with the retentate port(s). The retentate manifold 142 receives feed fluid from the feed passages 124, allowing retentate to exit the module 100. In other embodiments, the retentate outlet arrangement may have other configurations, for example, as an axial channel extending through the separation module.

The separation elements 10 may be stacked and sealed to one another and/or any other structural elements, e.g., the end plates, in a variety of ways to form the separation module. For example, a plurality of separation elements may be stacked, e.g., disposed adjacent to one another, and a sealing arrangement, e.g., gaskets, sealants, adhesives, heat seals, or solvent bonds may be disposed or formed between adjacent structural members, e.g., between adjacent peripheral regions of the structural members, to form a fluid tight seal between adjacent separation elements. In some embodiments, the permeable membrane and/or any intermediate layer may extend beyond the active region of the structural member into the peripheral region. In these embodiments, the permeable membrane and/or intermediate layer may be further held against the structural member and sealed at their periphery, i.e. outside of the active region, by the sealing arrangement. In many embodiments, the peripheral regions of the structural members, once stacked and sealed to one another, may form a robust containment structure, isolating the fluid streams from the ambient environment and providing a boundary, e.g., a pressure barrier, between the active regions of the separation elements and the ambient environment. In some embodiments, one or more fastening mechanisms, such as tie rods, bolts, and/or clamps, may also be used to secure the elements and/or the end plates of the separation module to one another.

While various aspects of the invention have previously been described and illustrated in the Figures, the invention is not limited to these embodiments. For instance, the invention is not limited to the previously described methods of making a separation element. In some embodiments, the permeable polymeric membrane may be thermally bonded to a polymeric structural member to which one or more intermediate layers have previously been thermally bonded. For example, registering at least one permeable polymeric membrane may include positioning the membrane adjacent an intermediate layer which is thermally bonded to the bonding sites of a structural member in the active region. The intermediate layer may be bonded to the structural member by methods similar to those previously described for thermally bonding a permeable membrane to the polymeric structural member. However, the interface regions may penetrate entirely through the intermediate layer. For example, the intermediate layer may be registered with the structural member, e.g. aligned, so that the intermediate layer overlies the bonding sites in the active region of the structural member. The structural member including the bonding sites may be heated, e.g. before or after registering the intermediate layer with the structural member, to a temperature at or above the softening temperature of the polymeric component or components of the structural member. Pressure may then be applied to press the softened polymeric component or components of the bonding sites into contact with the intermediate layer and the softened polymeric component may be resolidified in the interface regions in contact with, e.g. on or within, the intermediate layer.

The permeable polymeric membrane may then be thermally bonded to the structural member including the intermediate layer substantially as previously described. For example, the permeable polymeric membrane may be registered with the active region of the structural member, and the bonding sites of the structural member may be heated again to a temperature at or above the softening temperature of the polymeric component or components of the structural member. Pressure may then be applied to press the permeable membrane, intermediate layer, and structural member and to force the softened bonding sites through the bonded intermediate layer and into contact with the permeable polymeric membrane, i.e. the separation region. The softened polymeric component of the bonding sites may then be resolidified in contact with, e.g. on and/or within, the separation region of the permeable membrane to thermally bond the permeable polymeric membrane to the structural member.

All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

WE CLAIM:

1. A separation element comprising:

a polymeric structural member including at least one polymeric component having a softening temperature and an active region including a plurality of protrusions defining one or more passageways, the protrusions including at least one bonding site, and

a permeable polymeric membrane having a pore structure which permits fluid to flow through the membrane, wherein the permeable polymeric membrane has a softening temperature higher than the softening temperature of the polymeric component of the structural member, and the permeable polymeric membrane is thermally bonded to the polymeric structural member at the bonding sites, the polymeric component at the bonding sites being resolidified in contact with the permeable polymeric membrane without substantially collapsing the pore structure of the membrane in the active region.

2. The separation element according to claim 1 wherein the polymeric structural member includes first and second sides, each side having an active region including a plurality of protrusions defining one or more passageways and including at least one bonding site, and a first permeable polymeric membrane is thermally bonded to the bonding sites on the first side of the polymeric structural member and a second permeable polymeric membrane is thermally bonded to the bonding sites on the second side of the polymeric structural member, the polymeric component at the bonding sites on the first and second sides of the polymeric structural member being resolidified in contact with the first and second permeable polymeric membranes, respectively, without substantially collapsing the pore structure of the membranes in the active region.

3. The separation element according to claim 1 wherein the permeable polymeric membrane includes a separation region and a support region and the polymeric structural member is thermally bonded to the separation region.

4. The separation element according to claim 1 wherein a polymeric component of the polymeric structural member comprises polysulfone and the permeable polymeric membrane comprises a polyethersulfone membrane.

5. The separation element according to claim 1 wherein a polymeric component of the polymeric structural member comprises polypropylene and the permeable polymeric membrane comprises a polyethersulfone membrane.

6. The separation element according to claim 1 wherein a polymeric component of the polymeric structural member comprises polyetherimide and the permeable polymeric membrane comprises a polyethersulfone membrane.

7. The separation element according to claim 1 wherein a polymeric component of the polymeric structural member comprises polypropylene and the permeable polymeric membrane comprises a polyvinyldene fluoride membrane.

8. The separation element according to claim 1 wherein a polymeric component of the polymeric structural member comprises polypropylene and the permeable polymeric membrane comprises a nylon membrane.

9. The separation element according to any of the above claims wherein the permeable polymeric membrane includes no resolidified membrane matrix material.

10. The separation element according to claim 1 further comprising one or more intermediate layers disposed between the permeable polymeric membrane and the polymeric structural member.

11. A method of making a separation element comprising:

registering a permeable polymeric membrane and a polymeric structural member, wherein the permeable polymeric membrane has a pore structure which permits fluid to flow through the membrane and overlies an active region of the polymeric structural member including a plurality protrusions, the protrusions including at least one bonding site;

heating the bonding sites of polymeric structural member to a temperature at or above a softening temperature of at least one polymeric component of the polymeric structural member and below the softening temperature of the permeable polymeric membrane, including at least softening the polymeric component of the polymeric structural member at the bonding sites; and

applying pressure to the permeable polymeric membrane and the polymeric structural member in the vicinity of the bonding sites, including resolidifying the polymeric component at the bonding sites in contact with the permeable polymeric membrane to thermally bond the permeable polymeric membrane to the polymeric structural member, without substantially collapsing the pore structure of the membrane in the active region.

12. The method according to claim 11 wherein the bonding sites of the polymeric structural member are heated after registering the permeable polymeric membrane and the polymeric structural member and the permeable polymeric membrane is heated to a temperature below the softening temperature of the membrane.

13. The method according to claim 11 wherein resolidifying the polymeric component at the bonding sites in contact with the permeable membrane comprises resolidifying the component in contact with a separation region of the membrane.

FIG. 1

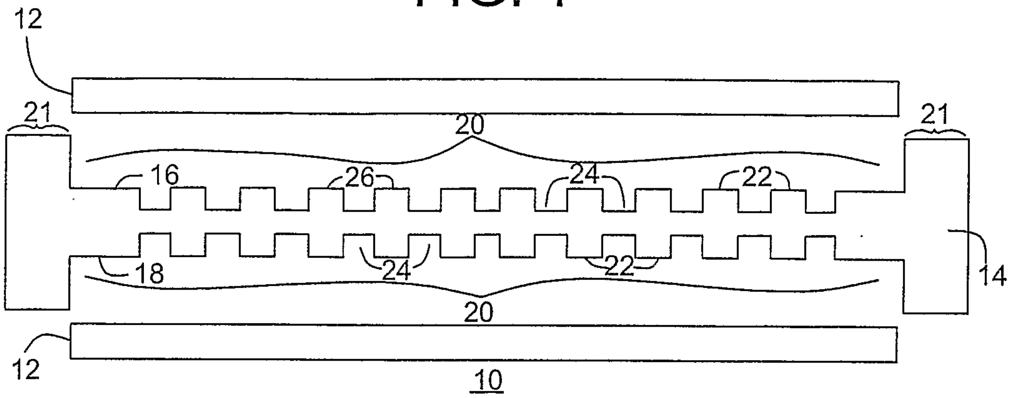
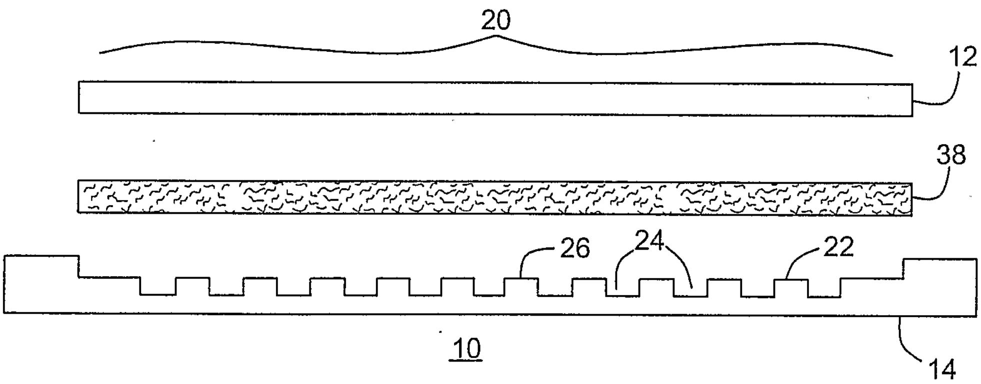


FIG. 5



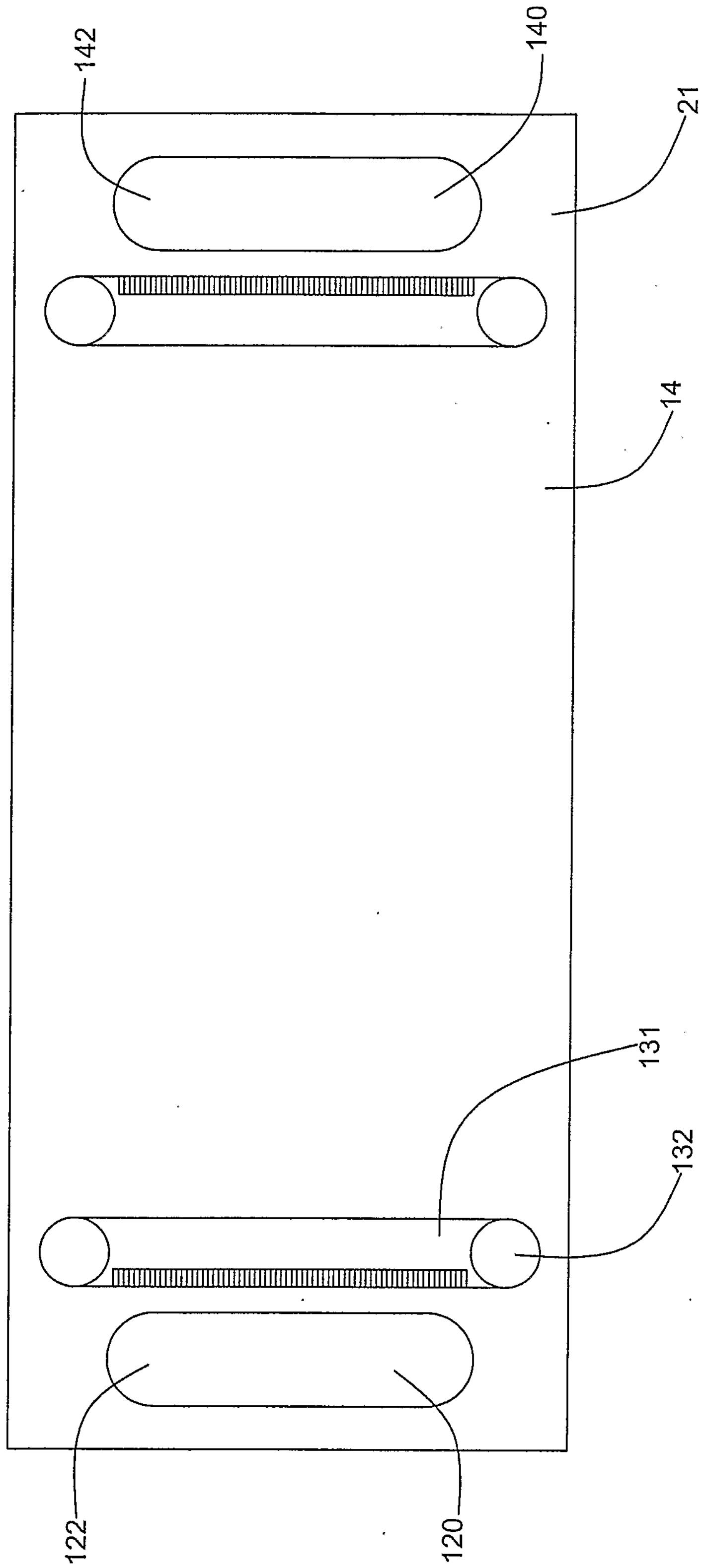


FIG. 2

FIG. 3

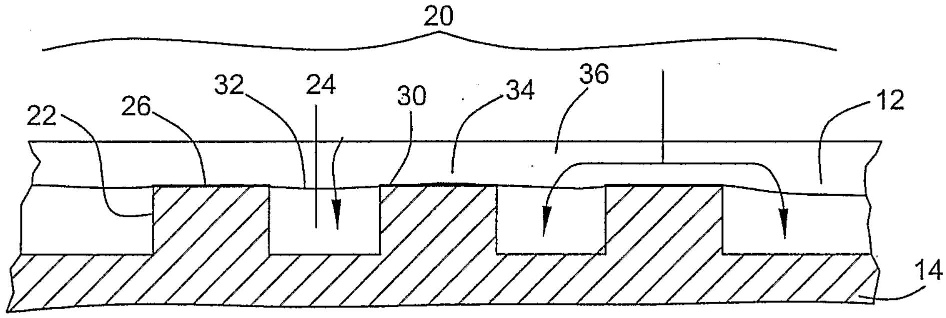


FIG. 4a

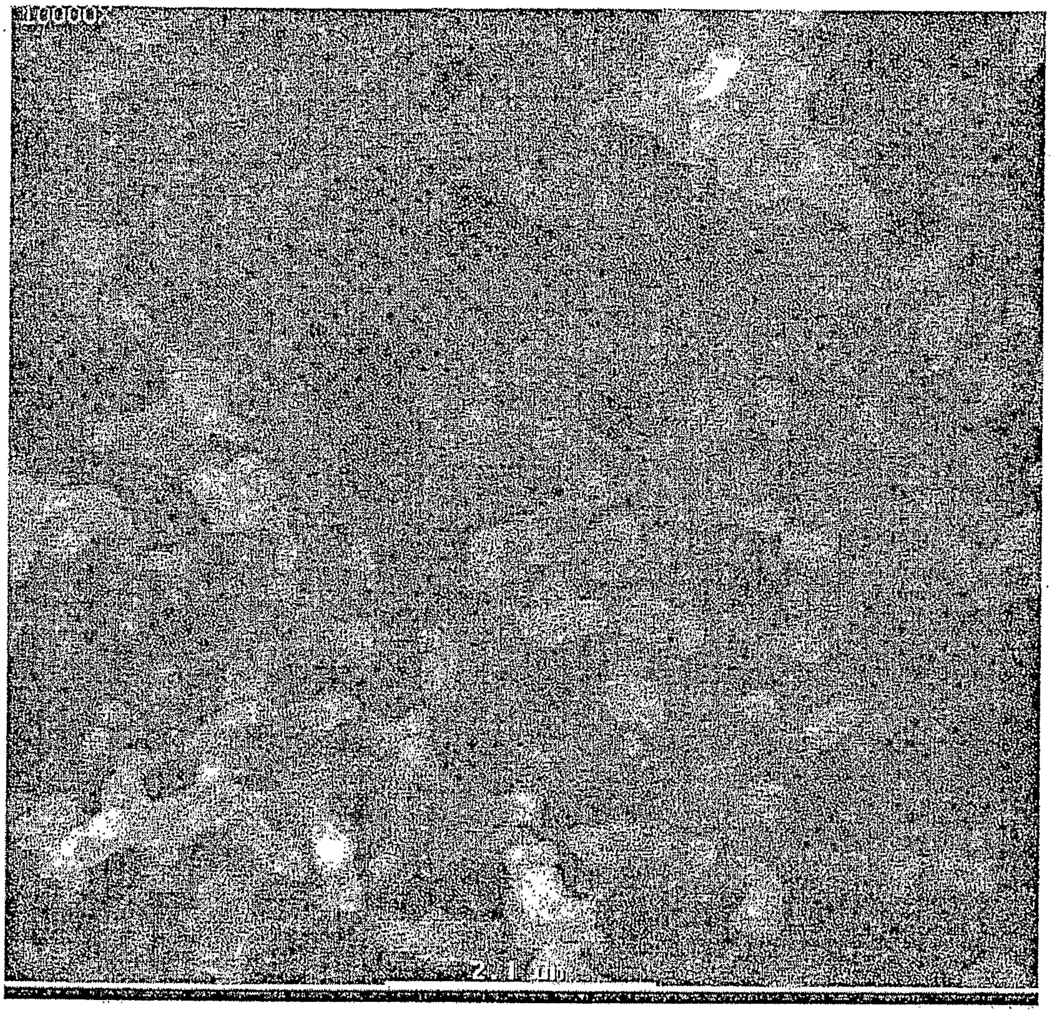
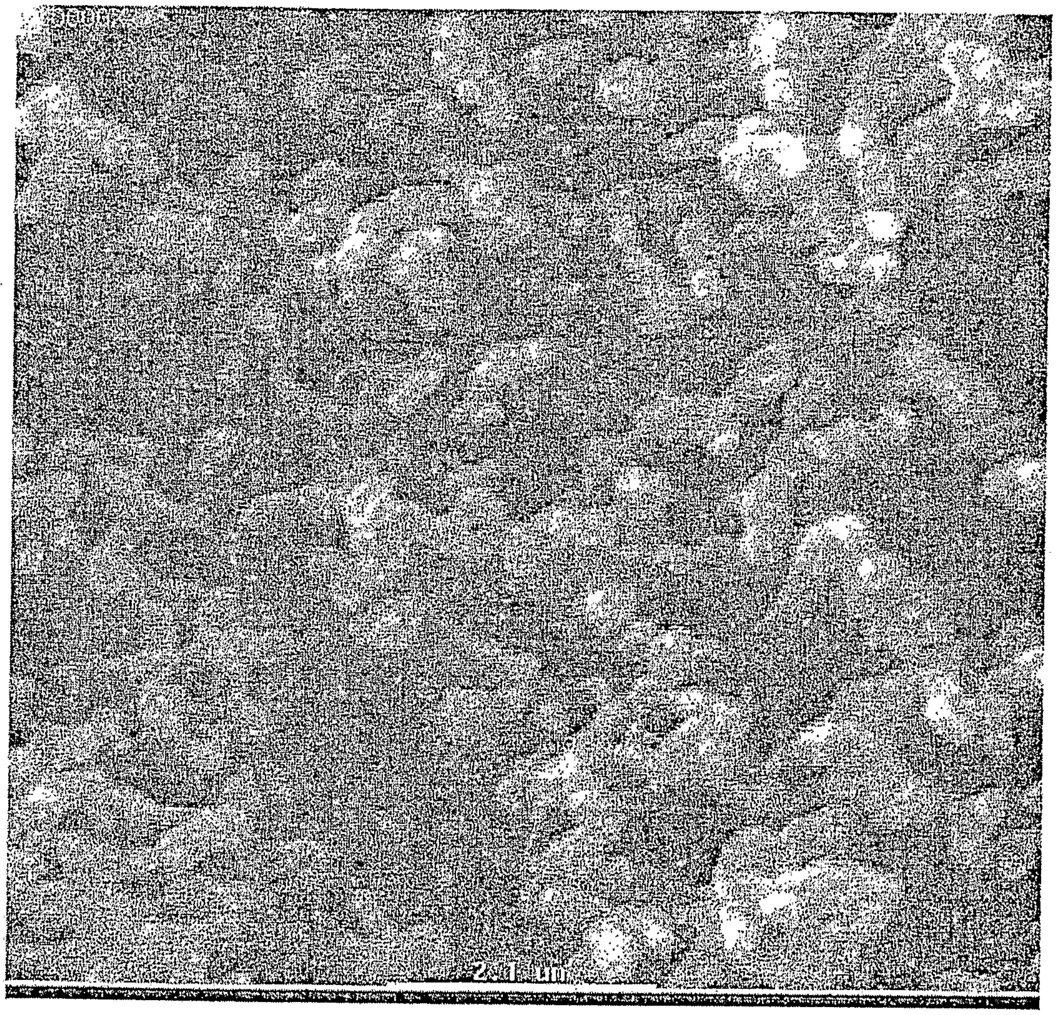


FIG. 4b



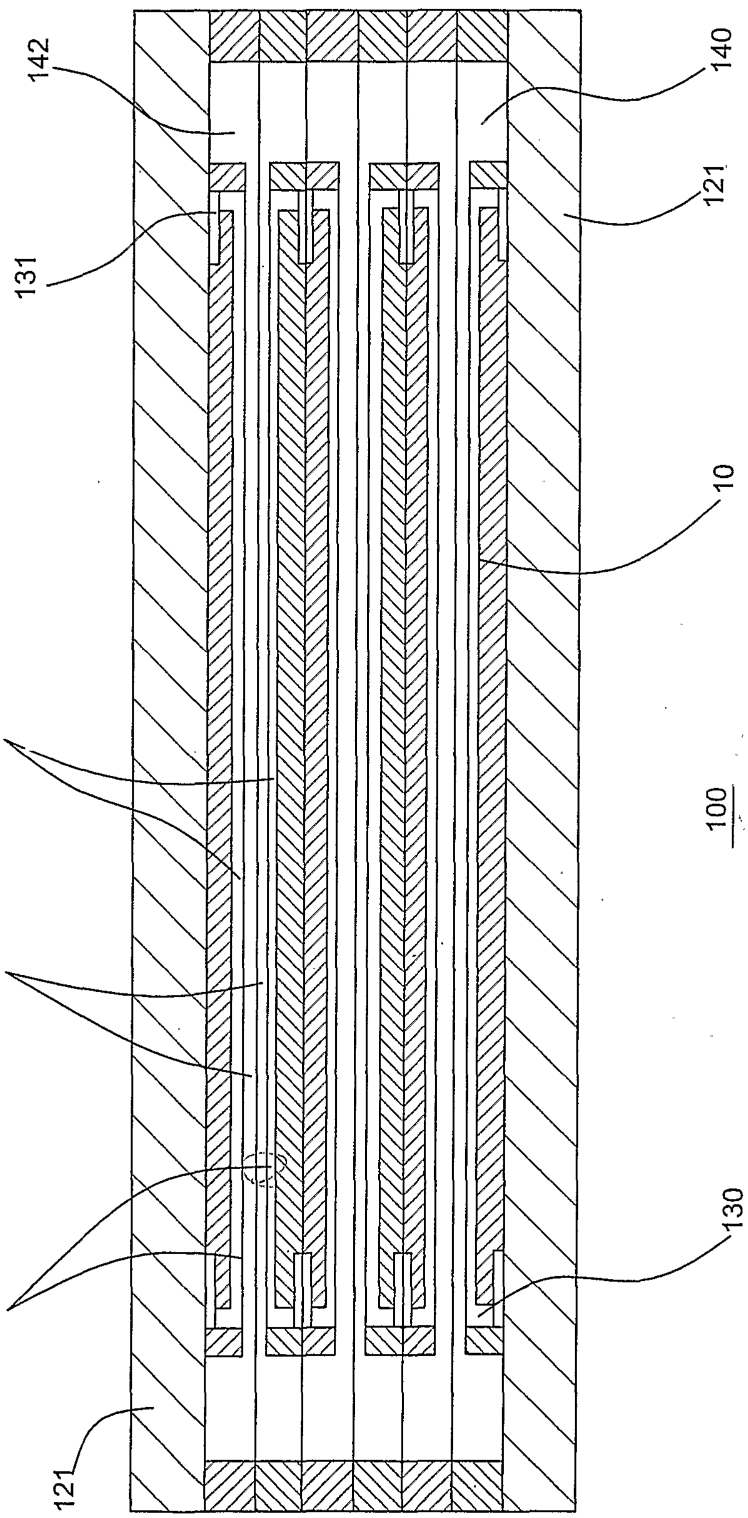


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2005/037104

A. CLASSIFICATION OF SUBJECT MATTER
B01D69/10 B01D65/00 B32B37/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B01D B32B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	WO 2004/103535 A (3M INNOVATIVE PROPERTIES COMPANY) 2 December 2004 (2004-12-02) page 7, line 9 - line 14; figures 1-8 page 8, line 14 - page 9, line 20	1-3,5,7, 9-13
X	US 5 651 888 A (SHIMIZU ET AL) 29 July 1997 (1997-07-29) column 6, line 32 - column 8, line 59; figures 15-19	1-3,9-13
X	US 2003/104192 A1 (HESTER JONATHAN F ET AL) 5 June 2003 (2003-06-05) paragraph '0042! - paragraph '0045! paragraphs '0056!, '0061!, '0065!, '0072!; figures 1-6; examples 1,2	1-3,5,7, 9,11-13
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 February 2006	22/02/2006

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Eijkenboom, A

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2005/037104

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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X	US 6 110 249 A (MEDCALF ET AL) 29 August 2000 (2000-08-29) column 1, line 55 - column 2, line 59 column 3, line 48 - column 4, line 18 column 10, line 49 - column 11, line 9; figures 4-18 -----	1,3,9, 11-13
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A	US 2003/194547 A1 (FUHRMANN LOUIS P ET AL) 16 October 2003 (2003-10-16) column 5, line 46 - line 48 column 7, line 41 - line 45; figures 2-6 -----	1-13

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
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