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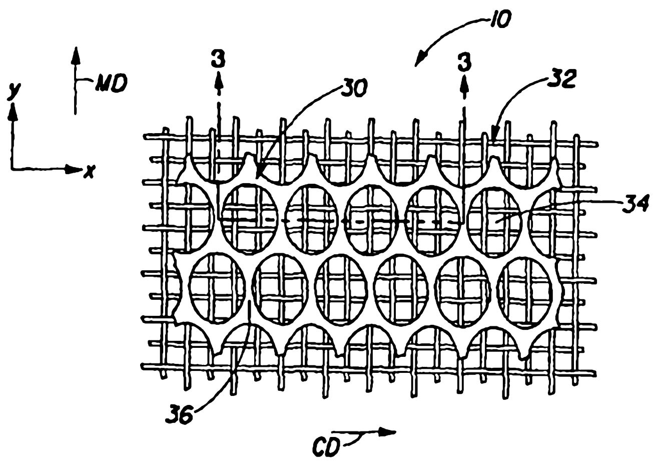
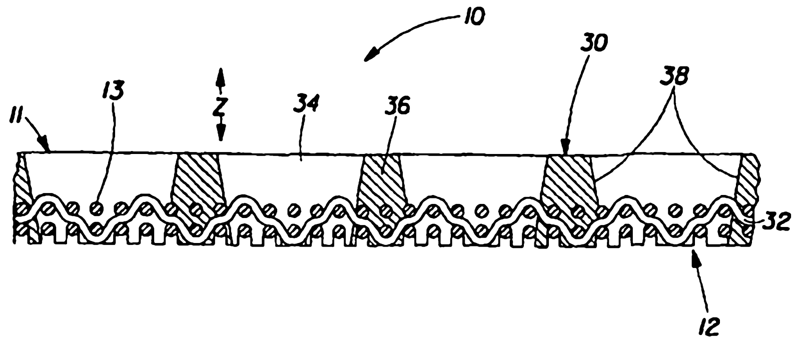
(54) Title: HIGH CALIPER PAPER AND PAPERMAKING BELT FOR PRODUCING THE SAME

(57) Abstract

A papermaking belt for producing a high caliper web of papermaking fibers and the paper web produced thereby. The papermaking belt comprises a reinforcing structure having a continuous network region and a plurality of discrete deflection conduits disposed thereon. The deflection conduits are sized, shaped, and arranged to maximize fiber deflection along the periphery of the conduits. The conduits are generally elliptical in shape having a mean width sized relative to mean fiber length. The conduits are arranged to maximize perimeter and corresponding fiber deflection per unit area.





HIGH CALIPER PAPER AND PAPERMAKING BELT FOR PRODUCING THE SAME

FIELD OF THE INVENTION

The present invention is related to papermaking belts useful in papermaking machines for making low density, soft, absorbent paper products and the paper products produced thereby. More particularly, this invention is concerned with papermaking belts comprising a patterned framework and a reinforcing structure and the high caliper/low density paper products produced thereby.

BACKGROUND OF THE INVENTION

Cellulosic fibrous webs such as paper are in use today for paper towels, toilet tissue, facial tissue, napkins and the like. The large demand for such paper products has created a demand for improved versions of the products and the methods of their manufacture.

In order to meet the needs of the consumer, cellulosic fibrous webs must exhibit several characteristics. They must have sufficient tensile strength to prevent the structures from tearing or shredding during ordinary use or when relatively small tensile forces are applied. The cellulosic fibrous webs must be absorbent, so that liquids may be quickly absorbed and fully retained by the fibrous structure.

Tensile strength is the ability of the cellulosic fibrous web to retain its physical integrity during use. Tensile strength is a function of the basis weight of the cellulosic fibrous web.

Absorbency is the property of the cellulosic fibrous web which allows it to attract and retain contacted fluids. Absorbency is influenced by the density of the cellulosic fibrous web. If the web is too dense, the interstices between fibers may be too small and the rate of absorption may not be great enough for the intended use. If the interstices are too large, capillary attraction of contacted fluids is minimized preventing fluids from being retained by the cellulosic fibrous web due to surface tension limitations.

Also, the web should exhibit softness, so that it is tactilely pleasant and not harsh during use. Softness is the ability of the cellulosic fibrous web to impart a particularly desirable tactile sensation to the user's skin. Softness is universally proportional to the ability of the cellulosic fibrous web to resist deformation in a direction normal to the plane of the cellulosic fibrous web.

Caliper is the apparent thickness of a cellulosic fibrous web measured under a certain mechanical pressure and is a function of basis weight and web structure. Strength, absorbency, and softness are influenced by the caliper of the cellulosic fibrous web.

Processes for the manufacturing of paper products generally involve the preparation of an aqueous slurry of cellulosic fibers and subsequent removal of water from the slurry while contemporaneously rearranging the fibers to form an embryonic web. Various types of machinery can be employed to assist in the dewatering process. A typical manufacturing process employs a Fourdrinier wire papermaking machine where the paper slurry is fed onto a surface of a traveling endless belt where the initial dewatering and rearranging of fibers is carried out.

After the initial forming, the paper web is carried through a drying process on another fabric referred to as the drying fabric which is in the form of an endless belt. The drying process can involve mechanical compaction of the paper web, vacuum dewatering, through air drying, and other types of processes. During the drying process, the embryonic web takes on a specific pattern or shape caused by the arrangement and deflection of cellulosic fibers.

One previous method introduced a papermaking belt comprising a foraminous woven member which was surrounded by hardened photosensitive resin framework. The resin framework was provided with a plurality of discrete, isolated channels known as deflection conduits. The papermaking belt used in the process was termed a deflection member because the papermaking fibres deflected into conduits and became rearranged therein upon the application of a fluid pressure differential. The utilisation of the belt in the papermaking process provided the possibility of creating paper having certain desired characteristics of strength, absorption, and softness.

Another method produced paper characterised by having two physically distinct regions distributed across its surfaces. One region is a continuous network region which has a relatively high density and high intrinsic strength. The other region is one which is comprised of a plurality of domes which are completely encircled by the network region. The domes in the latter region have relatively low densities and relatively low intrinsic strength compared to the network region.

The domes are produced as fibers fill the deflection conduits of the papermaking belt during the papermaking process. The deflection conduits prevent the fibers depositing therein from being compacted as the paper web is compressed during the drying process. As a result, the domes are thicker having a lower density and intrinsic strength compared to the compacted regions of the web. Consequently, the caliper of the paper web is limited by the intrinsic strength of the domes.

Once the drying phase of the papermaking process is finished, the arrangement and deflection of fibers is complete. However, depending on the type of the finished product, paper may go through additional processes such as calendering, softener application, and converting. These processes tend to compact the dome regions of the paper and reduce the thickness. Thus, producing high caliper finished paper products having two physically distinct regions requires forming cellulosic fibrous structures in the domes having a resistance to mechanical pressure.

As the cellulosic fibrous web is formed, the fibers are predominantly oriented in the X-Y plane of the web providing negligible Z-direction structural rigidity. Once the fibers oriented in the X-Y plane are compacted by mechanical pressure, the fibers are pressed together increasing the density of the paper web while decreasing the thickness. Orienting fibers in the Z direction of the web, enhances the web's Z-direction structural rigidity and its corresponding resistance to mechanical pressure. Accordingly, maximizing fiber orientation in the Z-direction maximizes caliper.

Deflection conduits provide a means for producing a Z-direction fiber orientation by enabling the fibers to deflect along the periphery of the deflection conduits. The total fiber deflection is dependent on the size and shape of the deflection conduits relative to the fiber length.

Large conduits allow smaller fibers to accumulate in the bottom of the conduit which in turn limits the deflection of subsequent fibers depositing therein. Conversely, small conduits allow large fibers to bridge across the conduit opening with minimal fiber deflection.

The shape of the conduits also influences fiber deflection. For instance, deflection conduits defined by a periphery forming sharp corners or small radii increase the potential for fiber bridging which minimises fiber deflection.

The above discussion of documents, acts, materials, devices, articles and the like is included in this specification solely for the purpose of providing a context for the present invention. It is not suggested or represented that any of these matters formed part of the prior art base or were common general knowledge in the field relevant to the present invention as it existed in Australia before the priority date of each claim of this application.

According the present invention provides a papermaking belt comprising a continuous network region and a plurality of discrete deflection conduits which are sized and shaped to optimise fibre deflection and corresponding Z-direction fiber orientation.

The invention further provides a paper web comprising an essentially continuous, essentially macroscopically monoplanar network region and a plurality of discrete domes dispersed therethroughout. The domes are sized and shaped to yield optimum calliper.

SUMMARY OF THE INVENTION

According to the present invention there is provided a paper making belt having a paper web contacting surface for carrying a web of papermaking fibers having a mean fiber length, $\overline{L}$, and a paper machine contacting surface opposite said web contacting surface, said papermaking belt including:

a reinforcing structure have a patterned framework disposed thereon, said patterned framework including a continuous network region and a plurality of discrete deflection conduits, said defection conduits isolated one from another by said continuous network region, said deflection conduits having a curvilinear periphery generally elliptical in shape with a mean width, $\overline{W}$, where $\overline{L}<\overline{W}<3\overline{L}$, an aspect ratio ranging from at least about 1.0 to about 2.0, and a minimum radius of curvature wherein the ratio of minimum radius of curvature to mean width ranges from at least about 0.29 to about 0.50.

According to another aspect of the present invention there is provided a papermaking belt having a paper web contacting surface for carrying a web of papermaking fibers having a mean fiber length, $\overline{L}$, and a paper machine contacting surface opposite said web contacting surface, said papermaking belt including:

a reinforcing structure having a patterned framework disposed thereon, said patterned framework including a continuous network region and a plurality of discrete deflection conduits, said deflection conduits isolated one from another by said continuous network region; said deflection conduits having a rectilinear periphery including wall segments forming a generally elliptical shape with a mean width, $\overline{W}$, where $\overline{L}<\overline{W}<3\overline{L}$, an aspect ratio ranging from a least about 1.0 to about 2.0 and an included angle between adjacent wall segments of at least about 120 degrees.

BRIEF DESCRIPTION OF THE DRAWING

These and other features, aspects and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings where:

FIG. 1 is a schematic side elevational view of one embodiment of a papermaking machine which uses the papermaking belt of the present invention.

FIG. 2 is a top plan view of a portion of the papermaking belt of the present invention, showing the framework joined to the reinforcing structure and having elliptically-shaped paper-side openings of the deflection conduits.

FIG. 3 is a vertical cross-sectional view of a portion of the papermaking belt shown in FIG. 2 as taken along line 3--3.

FIG. 4 is a vertical cross-sectional view of a portion of the papermaking belt shown in FIG. 3 depicting fibers bridging the deflection conduit.

FIG. 5 is a vertical cross-sectional view of a portion of the papermaking belt shown in FIG. 3 depicting fibers collecting in the bottom of the deflection conduit.

FIG. 6 is a vertical cross-sectional view of a portion of the papermaking belt shown in FIG. 3 depicting a fiber cantilevered over the deflection conduit opening to illustrate fiber defection.

FIG. 7 is a vertical cross-sectional view of a portion of the papermaking belt shown in FIG. 3 depicting a fiber bridging the deflection conduit opening to illustrate fiber defection.

FIG. 8a & 8b are a top plan views of conduit shapes having tight radii or sharp corners making them prone to fiber bridging.

FIG. 9 is a schematic representation of an elliptically shaped conduit having a rectilinear periphery.

FIG. 10 is a schematic representation of an elliptically shaped conduit having a curvilinear periphery.

FIG. 11 is a top plan schematic representation of deflection conduits arranged in a hexagonal pattern with major axes oriented parallel to the machine direction of the belt.

FIG. 12 is a top plan schematic representation of deflection conduits arranged in a hexagonal pattern with major axes oriented diagonal to the machine direction of the belt.

FIG. 13 is a vertical cross-sectional view of a portion of the papermaking belt shown in FIG. 3 depicting fibers deflecting into the deflection conduit and illustrating the relation between the conduit width, the conduit Z-direction height , and the web stretch.

Figure 14 is a vertical cross-sectional view of a portion of the papermaking belt shown in FIG. 3 depicting fibers deflecting into the deflection conduit and illustrating the relation between the web deflection angle and the angle forming the knuckle/conduit opening interface.

Figure 15 is a top plan schematic representation of a paper web having domes arranged in a hexagonal pattern.

Figure 16 is a vertical cross-sectional view of a portion of the paper web shown in FIG. 15 as taken along line 16--16.

DETAILED DESCRIPTION OF THE INVENTION

Definitions

As used herein, the following terms have the following meanings:

Machine direction, designated MD, is the direction parallel to the flow of the paper web through the papermaking equipment.

Cross machine direction, designated CD, is the direction perpendicular to the machine direction in the X-Y plane.

Center of area is a point within the deflection conduit that would coincide with the center of mass of a thin uniform distribution of matter bounded by the periphery of the deflection conduit.

Major axis is the longest axis crossing the center of area of the conduit and joining two points along the perimeter of the conduit.

Minor axis is the shortest axis or width crossing the center of area of the conduit and joining two points along the perimeter of the conduit.

Aspect Ratio is the ratio of the major axis length to the minor axis length.

The mean width of the conduit is the average length of straight lines drawn through the center of area of the conduit and joining two points on the perimeter thereof.

Radius of curvature is the instantaneous radius of curvature at a point on a curve.

Curvilinear pertains to curved lines.

Rectilinear pertains to straight lines.

Z-direction height is the portion of the resin framework extending from the paper facing side of the reinforcing structure.

Mean fiber length is the length weighted average fiber length.

The specification contains a detailed description of (1) the papermaking belt of the present invention and (2) the finished paper product of the present invention.

(1) <u>The Papermaking Belt</u>

In the representative papermaking machine schematically illustrated in FIG. 1, the papermaking belt of the present invention takes the form of an endless belt, papermaking belt 10. The papermaking belt 10 has a paper-contacting side 11 and a backside 12 opposite the paper-contacting side 11. The papermaking belt 10 carries a paper web (or "fiber web") in various stages of its formation (an embryonic web 27 and an intermediate web 29). Processes of forming embryonic webs are described in many references, such as U.S. Pat. No. 3,301,746, issued to Sanford and Sisson on Jan. 31, 1974, and U.S. Pat. No. 3,994,771, issued to Morgan and Rich on Nov. 30, 1976, both incorporated herein by reference. The papermaking belt 10 travels in the direction indicated by directional arrow B around the return rolls 19a and 19b, impression nip roll 20, return rolls 19c, 19d, 19e, 19f, and emulsion distributing roll 21. The loop around which the papermaking belt 10 travels includes a means for applying a fluid pressure differential to the embryonic web 27, such as vacuum pickup shoe (PUS) 24a and multi-slot vacuum box 24. In FIG. 1, the papermaking belt 10 also travels around a predryer such as blow-through dryer 26, and passes between a nip formed by the impression nip roll 20 and a Yankee drying drum 28.

Although the preferred embodiment of the papermaking belt of the present invention is in the form of an endless belt 10, it can be incorporated into numerous other forms which include, for instance, stationary plates for use in making handsheets or rotating drums for use with other types of continuous process. Regardless of the physical form which the papermaking belt 10 takes for the execution of the claimed invention, it generally has certain physical characteristics set forth below. The papermaking belt 10 of the present invention may be made according to commonly assigned U.S. Pat. No.

5,334,289, issued in the name of Trokhan et al., which patent is incorporated by reference herein.

As shown in Figure 2, the belt 10 according to the present invention comprises two primary components: a framework 30 and a reinforcing structure 32. The framework 30 preferably comprises a cured polymeric photosensitive resin. The framework 30 and belt 10 have a first surface 11 which defines the paper contacting side 11 of the belt 10 and an opposed second surface 12 oriented towards the papermaking machine on which the belt 10 is used.

As used herein, X, Y and Z directions are orientations relating to the papermaking belt 10 of the present invention (or paper web 27 disposed on the belt) in a Cartesian coordinate system. The papermaking belt 10 according to the present invention is macroscopically monoplanar. The plane of the papermaking belt 10 defines its X-Y directions. Perpendicular to the X-Y directions and the plane of the papermaking belt 10 is the Z-direction of the belt 10. Likewise, the web 27 according to the present invention can be thought of as macroscopically monoplanar and lying in an X-Y plane. Perpendicular to the X-Y directions and the plane of the web 27 is the Z-direction of the web 27.

Preferably the framework 30 defines a predetermined pattern and provides a knuckle area 36 which imprints a like pattern onto the web 27 of the present invention. A particularly preferred pattern for the framework 30 is an essentially continuous network. If the preferred essentially continuous network pattern is selected for the framework 30, discrete deflection conduits 34 will extend between the first surface 11 and the second surface 12 of the belt 10. The essentially continuous network surrounds and defines the deflection conduits 34.

The framework 30 prints a pattern corresponding to that of the framework 30 onto the web 27 carried thereon. Imprinting occurs anytime the belt 10 and web 27 pass between two rigid surfaces having a clearance sufficient to cause imprinting. This generally occurs in a nip between two rolls and most commonly occurs when the belt 10 transfers the paper to a Yankee drying drum 28. Imprinting is caused by compression of the framework 30 against the paper 27 at the pressure roll 20.

The first surface 11 of the belt 10 contacts the web 27 carried thereon. During papermaking, the first surface of the belt 10 may imprint a pattern onto the web 27 corresponding to the pattern of the framework 30.

The second surface 12 of the belt 10 is the machine contacting surface of the belt 10. The second surface may be made with a backside network having passageways therein which are distinct from the deflection conduits 34. The passageways provide irregularities in the texture of the backside of the second surface of the belt 10. The passageways allow for air leakage in the X-Y plane of the belt 10, which leakage does not necessarily flow in the Z-direction through the deflection conduits 34 of the belt 10. Belts 10 incorporating such backside texturing may be made according to any of commonly assigned U.S. Patents: 5,098,522 issued March 24, 1992 to Smurkoski et al.; 5,364,504 issued November 15, 1994 to Smurkoski et al.; and 5,260,171 issued November 9, 1993 to Smurkoski et al., the disclosures of which are incorporated by reference.

The second primary component of the belt 10 according to the present invention is the reinforcing structure 32. The reinforcing structure 32, like the framework 30, has a first or paper facing surface 13 and a second or machine facing surface 12 opposite the paper facing surface. The reinforcing structure 32 is primarily disposed between the opposed surfaces of the belt 10 and may have a surface coincident the backside of the belt 10. The reinforcing structure 32 provides support for the framework 30. The reinforcing component is typically woven, as is well known in the art. The portions of the reinforcing structure 32 registered with the deflection conduits 34 prevent fibers used in papermaking from passing completely through the deflection conduits 34 and thereby reduces the occurrences of pinholes. If one does not wish to use a woven fabric for the reinforcing structure 32, a nonwoven element, screen, net, or a plate having a plurality of holes therethrough may provide adequate strength and support for the framework 30 of the present invention.

As shown in Figs. 3, the framework 30 is joined to the reinforcing structure 32. The framework 30 extends outwardly from the paper-facing side 13 of the reinforcing structure 32. The reinforcing structure 32 strengthens the resin framework 30 and has suitable projected open area to allow the vacuum dewatering machinery employed in the papermaking process to perform adequately its function of removing water from the embryonic web 27, and to permit water removed from the embryonic web 27 to pass through the papermaking belt 10.

The belt 10 according to the present invention may be made according to any of commonly assigned U.S. Patents: 4,514,345, issued April 30, 1985 to Johnson et al.; 4,528,239, issued July 9, 1985 to Trokhan; 5,098,522, issued March 24, 1992; 5,260,171, issued Nov. 9, 1993 to Smurkoski et al.; 5,275,700, issued Jan. 4, 1994 to Trokhan; 5,328,565, issued July 12, 1994 to Rasch et al.; 5,334,289, issued Aug. 2, 1994 to Trokhan et al.; 5,431,786, issued July 11, 1995 to Rasch et al.; 5,496,624, issued March 5, 1996 to Stelljes, Jr. et al.; 5,500,277, issued March 19, 1996 to Trokhan et al.; 5,514,523, issued May 7, 1996 to Trokhan et al.; 5,554,467, issued Sept. 10, 1996, to Trokhan et al.; 5,566,724, issued Oct. 22, 1996 to Trokhan et al.; 5,624,790, issued April 29, 1997 to Trokhan et al.; 5,628,876 issued May 13, 1997 to Ayers et al.; 5,679,22 issued Oct. 21, 1997 to Rasch et al.; and 5,714,041 issued Feb. 3, 1998 to Ayers et al., the disclosures of which are incorporated herein by reference.

The ability to produce a paper web having a particular thickness is a function of the caliper of the web. Caliper is the apparent thickness of a cellulosic fibrous web measured under a certain mechanical pressure. Caliper is a function of web basis weight and web structure. Basis weight is the weight in pounds of 3000 square feet of paper. Web structure pertains to orientation and density of fibers making up the web 27.

Fibers making up the web 27 are typically oriented in the X-Y plane and provide minimal structural support in the Z-direction. Thus, as the web 27 is compressed by the patterned framework 30, the web 27 is compacted creating a patterned, high density region that is reduced in thickness. Conversely, portions of the web 27 covering the deflection conduits 34 are not compacted and as a result, thicker, low density regions are produced.

The low density regions, referred to as domes, give the web 27 an apparent thickness. Since the fibers making up a typical dome are predominently oriented in the X-Y plane of the web 27, the fibers provide negligible Z-direction support. Consequently, the domes are highly susceptible to being deformed and reduced in thickness during subsequent papermaking operations. Thus, the caliper of the web 27 is generally limited by the domes' ability to withstand mechanical pressure.

However, deflection conduits 34 provide a means for deflecting fibers in the Z-direction along the periphery 38. Fiber deflection produces a fiber orientation which includes a Z-direction component. Such fiber orientation not only creates an apparent web thickness but also provides certain amount of structural rigidity in the Z-direction which assists the web 27 in sustaining its thickness throughout the papermaking process. Accordingly, for the present invention, deflection conduits 34 are sized and shaped to maximize fiber deflection along the peripheries 38.

Water removal from the embryonic web 27 begins as the fibers 50 are deflected into the deflection conduits 34. The water removal results in a decrease in fiber mobility which tends to fix the fibers in place after they have been deflected and rearranged. Deflection of the fibers into the deflection conduits 34 can be induced by, the application of differential fluid pressure to the embryonic web 27. One preferred method of applying differential pressure is by exposing the embryonic web 27 to a vacuum through deflection conduits 34. In FIG. 1 the preferred method is illustrated by the use of pick-up shoe 24.

Without being limited by theory, it is believed that the rearrangement of the fibers in the embryonic web 27 relative to the deflection conduits 34 can generally take one of two models, dependent on a number of factors including fiber length. As schematically shown in FIG. 4, the ends of longer fibers 50 can be restrained on the top of the knuckles 36 allowing the middle parts of fibers 50 to be bent into the conduit 34 without being fully deflected. Thus, "bridging" of the deflection conduit 34 occurs. Alternatively, as shown in FIG. 5, fibers 50 (predominantly, the shorter ones) can actually be fully deposited into the conduit 34 with little, if any, deflection creating a pile of fibers 50 therein and minimizing the deflection of subsequent fibers depositing in and around the conduit 34.

Fiber deflection is function of the web's resistance to bending. The higher the web bending stiffness the greater the resistance to deflection. The bending stiffness of a web is dominated by two factors: (1) the bending stiffness of individual fibers; and (2) fiber-to-fiber bonding strength. However, the web at the pick-up shoe 24a is wet and the fiber-to-fiber bonds are not well established due to the presence of large amounts of water in the web. Thus, the dominant factor is the individual fiber stiffness. The stiffer the fiber the smaller the deflection.

Although fiber deflection is dependent on the inherent stiffness of the fibers 50, the magnitude of the deflection is largely determined by whether or not the fibers 50 are long enough to span the width of a conduit 34. Figures 6 and 7 show two possible scenarios of fiber deflection. In Figure 6, the fiber 50 is fixed at point A and cantilevered over the opening of the conduit 34. When this fiber 50 is subjected to a uniform load, such as a vacuum, the result is a high bending moment at point A and a deflection at point B defined by

$$f_B = F\ L^3/8EI \quad (1)$$

where,

f_B - deflection at point B;

F - Force uniformly distributed over the length of the fiber;

L - Length of a fiber from the point(s) of support;

E - Modulus of Elasticity;

I - moment of inertia

In Figure 7, the fiber segment 50 is longer than conduit width, resulting in two fixed points A and B. If the fiber segment 50 experiences the same vacuum, the supporting forces at A and B create offsetting bending moments resulting in a fiber deflection at point C defined by

$$f_C = F\ L^3/384EI \qquad (2)$$

where f_C is the fiber deflection at point C

Assuming that the parameters F, L, E, and I are the same for fibers shown in Figures 6 and 7, it is evident that the fiber deflection f_B is 48 times larger than the fiber deflection f_C.

$$f_B = 48\ f_C \qquad (3)$$

Accordingly, fiber deflection can be enhanced by sizing the deflection conduits 34 to minimize the occurrences of fiber bridging. However, the size of the conduit is also limited by the number of small fibers in the furnish capable of accumulating in the conduits 34 and consequently, inhibiting the larger fibers from deflecting therein.

Furnish normally includes both hardwood and softwood. An example of hardwood fiber is Eucalyptus (EUC) while an example of softwood fiber is Northern Softwood Kraft (NSK). An example of a furnish comprises 30% by weight softwood and 70% by weight hardwood. Since the average fiber length of softwood is about three times the average fiber length of hardwood, sizing the deflection conduits relative to the average softwood fiber length results in conduits that are highly susceptible to the accumulation of shorter hardwood fibers, thereby limiting the deflection of the longer fibers. Thus, it is preferred that the conduit width, W, be sized relative to the mean fiber length of the furnish, $\bar{L}$, where

$$W \geq \bar{L} \qquad (4).$$

For the present invention, the mean fiber length is the length weighted average fiber length determined by

$$\bar{L} = \frac{\sum n_i \overline{L_i^2}}{\sum n_i \overline{L_i}} \qquad (5)$$

where

L_i = Average lengths of fibers in class i.
n_i = Number of fibers measured in class i.

The length weighted average fiber length for the present invention is about 0.043 inches.

As shown in Figures 9 and 10, the conduits 34 may take on a variety of different shapes having either variable or constant widths. Conduit shapes having variable widths are defined in terms of the major axis 40, the minor axis 42, and the mean width 46. As defined, the major axis 40 is the longest axis or width crossing the center of area of the conduit, the minor axis 42 is the shortest width crossing the center of area of the conduit, and the mean width 46 is the average width crossing center of area of the conduit.

The mean width 46 is determined by first measuring the length of a line drawn through the center of area in the CD joining two points on the perimeter of the conduit. The lengths of similar lines oriented at $\Delta\theta$ angular increments with respect to the CD (such as 15 degrees or less ranging from 0° to 165° where 0° represents the CD) are measured and averaged to determine the mean width.

Since fiber bridging is most likely to occur along the minor axis 42, it is preferred to size the minimum width of the conduit 34 relative to the mean fiber length, $\overline{L}$, such that

$$W_{\min} \geq \overline{L} \qquad (6)$$

Therefore, for the present invention, the preferred min conduit width is at least about 0.043 inches.

Since the accumulation of smaller fibers can occur along both the major and minor axes 40, 42 of the conduit, it is difficult to define an upper limit for either or both axes 40, 42 resulting in minimal fiber accumulation and maximum fiber deflection. However, for the present invention, it has been found that sizing the conduits 34 such that the mean width 46 ranges between the mean fiber length $\overline{L}$ and three times the mean fiber length, $3\overline{L}$, results in maximum caliper generation.

$$\overline{L} < \overline{W} < 3\overline{L}$$

Accordingly, for the present invention, it is preferred to size the conduits such that the mean conduit width ranges from about 0.043 inches to about 0.129 inches.

The web 27 is approximately a two-dimensional fiber network. An ideal fiber network comprises a random distribution of fibers where the fiber orientation does not favor a particular direction. For such an ideal network, the mean fiber length, $\overline{L}$, is same in all directions.

However fiber networks are typically arranged in the web having a fiber orientation that is biased in a particular direction. For such biased networks, the mean fiber length will vary relative to angular orientation in the X-Y plane of the web 27. Theoretically, such mean fiber length is designated, $\overline{L_\theta}$, where

$$\overline{L}_\theta = \frac{1}{n}\sum_{i=1}^{n} L_{\theta_i} \qquad (7)$$

and

θ = the angular orientation in the X-Y plane relative to CD

L_{θ_i} = Component Lengths of fibers at angular orientation, θ, in X-Y plane.

$\overline{L_\theta}$ = Mean fiber length at angular orientation, θ, in X-Y plane.
n = Number of fibers measured at angular orientation, θ, in X-Y plane.

For the present invention, the fibers 50 making up the two dimensional fiber network are predominantly oriented in the machine direction MD. Consequently, the mean fiber length in the machine direction is greater than the mean fiber length in the cross machine direction CD.

$$\overline{L_{MD}} > \overline{L_{CD}} \qquad (8)$$

From equation 4, it follows that

$$W_{MD} > W_{CD} \qquad (9)$$

Thus, as shown in Figure 11, it is preferred to orient the conduits 34 such that the major axes 40 run parallel to the machine direction of the belt. However, since the fiber orientation typically favors the MD, one skilled in the art would appreciate that the major axis 40 may also be oriented at a diagonal, where, as illustrated in Figure 12, diagonal is defined as an angle 54 oriented 22.5° ± 22.5° relative to MD.

The shape of the conduit is defined in terms of an aspect ratio, R_A, which is defined as the ratio of the major axis 40 to the minor axis 42. For maximum deflection of fibers, it follows from equation (8) & (9) that the aspect ratio, R_A, be defined as

$$R_A = \frac{\overline{L_{MD}}}{\overline{L_{CD}}} = \frac{W_{MD}}{W_{CD}} \qquad (10)$$

However, it is not practical to measure the mean fiber length in a particular direction of the web in the X-Y plane for a web condition just prior to the fibers being deflected into the deflection conduits 34. Therefore, the inherent physical properties of the web which are a function of fiber length need to be considered in order to determine a preferred aspect ratio, R_A, for a conduit shape providing maximum fiber deflection.

The physical properties of a paper web 27 are largely influenced by the orientation of fibers in the X-Y plane of the web 27. For instance, a web 27 having a fiber orientation which favors MD, has a higher tensile strength in MD than in CD, a higher stretch in CD than in MD, and a higher bending stiffness in MD than in CD.

In addition to fiber orientation, the web tensile strength is proportional to the corresponding lengths of fibers oriented in a particular direction in the X-Y plane. Therefore, the web tensile strength in the MD and CD is proportional to the mean fiber lengths in the MD and CD.

$$T_{MD.CD} \text{ (Tensile Strength)} \propto \overline{L}_{MD.CD} \quad (11)$$

Accordingly, from equation 8, it follows that

$$T_{MD} > T_{CD} \quad (12)$$

Furthermore, by substituting $\frac{T_{MD}}{T_{CD}}$ for $\frac{\overline{L_{MD}}}{L_{CD}}$ in equation 10, the aspect ratio, R_A, defining the conduit shape is expressed as

$$R_A = \frac{T_{MD}}{T_{CD}} = \frac{W_{MD}}{W_{CD}} \quad (13)$$

The tensile strengths of the web 27 in MD and CD were measured using a Thwing-Albert Intelect II Standard Tensile Tester manufactured by Thwing-Albert Instrument Co. of Philadelphia, PA. Consequently, the preferred conduit shape providing optimum fiber deflection and corresponding caliper generation has an aspect ratio ranging from 1 to about 2. A more preferred shape has an aspect ratio ranging from about 1.3 to 1.7. A most preferred shape has an aspect ratio ranging from 1.4 to 1.6.

The shape of the deflection conduit 34 is not only significant for minimizing fiber bridging across the width of the conduit but also for minimizing fiber bridging along the perimeter 38 of the conduit walls. Conduit walls forming tight radii or sharp corners provide additional locations for fiber bridging. Examples of unfavorable conduit shapes for this purpose are shown in Figures 8a & 8b.

As shown in Figures 9 and 10, a preferred conduit shape for the present invention is one that is generally elliptical which includes, but is not limited to, circles, ovals, and polygons of six or more sides. Figure 9 illustrates an elliptically shaped conduit having a rectilinear periphery comprising individual wall segments 44. For such conduit shape, fiber bridging along the periphery is minimized by providing an included angle 39 between adjacent wall segments which is at least about 120 degrees.

Figure 10 illustrates an elliptically shaped conduit having a curvilinear periphery concave toward the center of the conduit. The curvilinear periphery includes a minimum radius of curvature 48. Similarly, fiber bridging along the periphery is minimized by limiting the shape such that the ratio of the minimum radius of curvature 48 to the mean conduit width is at least 0.29 and no more than 0.50.

$$0.29 \le \frac{r_{curv(min)}}{\overline{\overline{W}}} \le 0.50 \qquad (14)$$

As illustrated in Figure 13, ideally, the web 27 on top of the knuckle 36 experiences zero stretch, while above the conduits 34 the web 27 deflects fully therein experiencing an average stretch, ε,

where

$$\varepsilon \approx \frac{2OB}{W} \qquad (15)$$

and

ε = Average stretch

OB = is the Z-direction height

W = is the conduit width.

Critical stretch determines when the web 27 will break. If the stretch is greater than the critical stretch in the web 27, the network will be broken causing pinholes in the web. The critical stretch in the web 27 depends on the network properties such as fiber length and fiber orientation. The fiber-to-fiber bonding does not play a role in critical stretch because the web at the pick up shoe is wet and the fiber-to-fiber bonds are not well established.

The total distance the web 27 deflects into the conduits 34 is dependent on the Z-direction height 60. Since the critical stretch of the web is directly proportional to OB 60

, it follows that OB is limited by the critical stretch of the web 27. Accordingly, from equation 15 a reasonable range for OB 60 is expressed as

$$OB \leq \frac{\varepsilon_{critical}}{2} \mathrm{W} \qquad (16)$$

The critical stretch $\varepsilon_{critical}$ is a complicated function of fiber length, fiber orientation and basis weight. Qualitatively, the critical stretch increases when fiber length and/or basis weight increases. For the present invention, the preferred Z-direction height 60 for maximum web deflection ranges from at least about 0.005 inches to about 0.039 inches.

The total deflection a web will undergo in the deflection conduits is also largely determined by the angle forming the knuckle/conduit interface of the patterned framework. The web deflection angle 62 is defined as the angle of the web at the knuckle/conduit interface with respect to the Z-direction. An illustration of the web deflection is shown in Figure 14. Fibers 50 accumulating at the knuckle/conduit interface are oriented with a Z-direction component which enables them to provide the support structure capable of withstanding external compressive forces. Fibers oriented parallel to the Z-direction at the knuckle/conduit interface provide maximum support. However, since a web 27 is not infinitely flexible it is not capable of completely following the contour of the conduit 34. In addition, due to manufacturing limitations, the walls of the deflection conduits are sloped forming a resin angle 64 at the knuckle/conduit interface. The resin angle 64 further limits the web deflection since the deflection angle 62 cannot be less than the resin angle 64. For the present invention, the resin angle is preferably sloped between 5 degrees and 10 degrees. The web deflection angle typically ranges from about 20 degrees to about 50 degrees.

Since the external force applied to paper during the various processes are reacted by the supporting force from the fibers in the knuckle/pocket interface, the greater the number of fibers in this region the higher the supporting force and corresponding caliper. The number of fibers 50 in the transition interface can be optimized by maximizing the total perimeter 38 of the interface. This is equivalent to maximizing the number of deflection conduits 34 per unit area or to minimizing the percentage of knuckle area 36. Theoretically, conduits 34 can be packed to an extreme. However, as shown in Figures 11 and 12 the knuckles 36 separating conduits 34 are required to have a minimum width 52 in order to enable the resin to securely attach to the secondary 32. For the present invention, the preferred minimum knuckle width 52 ranges from at least about 0.007 inches to about 0.020 inches.

Furthermore, the number of conduits per unit area can be maximized by packing conduits 34 into more efficient arrangements. A preferred arrangement of conduits 34 is one forming a hexagonal pattern as shown in Figures 11 and 12.

(2) The Paper

The paper 80 of the present invention has two primary regions. The first region comprises an imprinted region 82 which is imprinted against the framework 30 of the belt 10. The imprinted region 82 preferably comprises an essentially continuous network. The continuous network 82 of the first region of the paper 80 is made on the essentially continuous framework 30 of the belt 10 and will generally correspond thereto in geometry and be disposed very closely thereto in position during papermaking.

The second region of the paper 80 comprises a plurality of domes 84 dispersed throughout the imprinted network region 82. The domes 84 generally correspond in geometry, and during papermaking, in position to the deflection conduits 34 in the belt 10. By conforming to the deflection conduits 34 during the papermaking process, the fibers in the domes 84 are deflected in the Z-direction between the paper facing surface of the framework 30 and the paper facing surface of the reinforcing structure 32. As a result, the domes 84 protrude outwardly from the essentially continuous network region 82 of the paper 80. The domes 84 are preferably discrete, isolated one from another by the continuous network region 82.

Without being bound by theory, it is believed the domes 84 and essentially continuous network regions 82 of the paper 80 may have generally equivalent basis weights. By deflecting the domes 84 into the deflection conduits 34, the density of the domes 84 is decreased relative to the density of the essentially continuous network region

82. Moreover, the essentially continuous network region 82 (or other pattern as may be selected) may later be imprinted as, for example, against a Yankee drying drum. Such imprinting increases the density of the essentially continuous network region 82 relative to that of the domes 84. The resulting paper 80 may be later embossed as is well known in the art.

The paper 80 according to the present invention may be made according to any of commonly assigned U.S. Patents: 4,529,480, issued July 16, 1985 to Trokhan; 4,637,859, issued Jan. 20, 1987 to Trokhan; 5,364,504, issued Nov. 15, 1994 to Smurkoski et al.; and 5,529,664, issued June 25, 1996 to Trokhan et al. and 5,679,222 issued Oct. 21, 1997 to Rasch et al., the disclosures of which are incorporated herein by reference.

The shapes of the domes 84 in the X-Y plane include, but are not limited to, circles, ovals, and polygons of six or more sides. Preferably, the domes 84 are generally elliptical in shape comprising either curvilinear or rectilinear peripheries 86. The curvilinear periphery 86 comprises a minimum radius of curvature such that the ratio of the minimum radius of curvature to mean width of the dome ranges from at least about 0.29 to about 0.50. The rectilinear periphery 86 may comprise of a number of wall segments where the included angle between adjacent wall segments is at least about 120 degrees.

Providing a paper 80 having high caliper requires maximizing the number Z-direction fibers per unit area in the web. The majority of the Z-direction fibers are oriented along the periphery 86 of the domes 84 where fiber deflection occurs. Thus, Z-direction fiber orientation and corresponding caliper of the paper web is largely dependent on the number of domes per unit area.

As shown in Figure 15, the number of domes 84 per unit area is maximized by minimizing the distance between adjacent domes which is accomplished by arranging the domes into efficient patterns. For the present invention, the preferred minimum distance 88 between domes 84 is at least about 0.007 inches and no more than 0.020 inches. The preferred arrangement of the domes 84 is one forming a hexagonal pattern.

The number of domes 84 per unit area of the paper 80 is largely dependent on the size and shape of the deflection conduits previously described. For the present invention, the preferred mean width of the domes 84 is at least about 0.043 inches and less than about 0.129 inches. The preferred generally elliptical shape for the domes is one having an aspect ratio ranging from 1 to about 2. A more preferred generally elliptical shape has an aspect ratio ranging from about 1.3 to 1.7. A most preferred generally elliptical shape has an aspect ratio ranging from 1.4 to 1.6.

The caliper of the paper web is typically measured under a pressure of 95 grams per square inch using a round presser foot having a diameter of 2 inches, after a dwell time of 3 seconds. The caliper can be measured using a Thwing-Albert Thickness Tester Model 89-100, manufactured by the Thwing-Albert Instrument Company of Philadelphia, Pennsylvania. The caliper is measured under TAPPI temperature and humidity conditions.

For the present invention, the caliper was measured on a paper web comprising two plies. The caliper of the two ply paper web is preferably between 20 mils and 40 mils. More preferably the caliper of the two ply paper web is between 38 mils and 46 mils. Most preferably the caliper of the two ply paper web is between 25 mils and 30 mils.

While particular embodiments of the present invention have been illustrated and described, it would be obvious to those skilled in the art that various other changes and modifications can be made without departing from the spirit and scope of the invention. It is intended to cover in the appended claims all such changes and modifications that are within the scope of the invention.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A paper making belt having a paper web contacting surface for carrying a web of papermaking fibers having a mean fiber length, $\overline{L}$, and a paper machine contacting surface opposite said web contacting surface, said papermaking belt including:

a reinforcing structure have a patterned framework disposed thereon, said patterned framework including a continuous network region and a plurality of discrete deflection conduits, said defection conduits isolated one from another by said continuous network region; said deflection conduits having a curvilinear periphery generally elliptical in shape with a mean width, $\overline{W}$, where $\overline{L}<\overline{W}<3\overline{L}$, an aspect ratio ranging from at least about 1.0 to about 2.0, and a minimum radius of curvature wherein the ratio of minimum radius of curvature to mean width ranges from at least about 0.29 to about 0.50.

2. A papermaking belt according to claim 1, wherein said patterned framework extends outwardly from said reinforcing structure a distance ranging from at least about 0.005 inches to about 0.039 inches.

3. A papermaking belt according to claim 1 or 2, wherein the deflection conduits are sloped from about 5 degrees to about 10 degrees.

4. A papermaking belt according to any one of the preceding claims, wherein said deflection conduits are arranged in a hexagonal pattern.

5. A papermaking belt according to any one of the preceding claims, wherein the continuous network region provides a knuckle area having a minimum width ranging from at least about 0.007 inches to about 0.020 inches.

6. A papermaking belt according to claim 5, wherein said knuckle area ranges from about 25% to about 50% of the web contacting surface of said belt.

7. A papermaking belt according to any one of the preceding claims, wherein said deflection conduits include major axes and said belt includes a machine direction in the X-Y plane, and wherein said major axes are oriented parallel to said machine direction.

8. A papermaking belt according to any one of claims 1 to 6, wherein said deflection conduits include major axes and said belt includes a machine direction in the X-Y plane, and wherein said major axes are oriented diagonal to said machine direction.

9. A papermaking belt according to any one of the preceding claims, wherein the aspect ratio of said deflection conduits ranges from about 1.3 to about 1.7.

10. A papermaking belt having a paper web contacting surface for carrying a web of papermaking fibers having a mean fiber length, $\overline{L}$, and a paper machine contacting surface opposite said web contacting surface, said papermaking belt including:

a reinforcing structure having a patterned framework disposed thereon, said patterned framework including a continuous network region and a plurality of discrete deflection conduits, said deflection conduits isolated one from another by said continuous network region; said deflection conduits having a rectilinear periphery including wall segments forming a generally elliptical shape with a mean width, $\overline{W}$, where $\overline{L}<\overline{W}<3\overline{L}$, an aspect ratio ranging from a least about 1.0 to about 2.0 and an included angle between adjacent wall segments of at least about 120 degrees.

11. A papermaking belt according to any one of the embodiments substantially as herein described and illustrated.

DATED: 22 January 2002

PHILLIPS ORMONDE & FITZPATRICK

Attorneys for:

THE PROCTER AND GAMBLE COMPANY

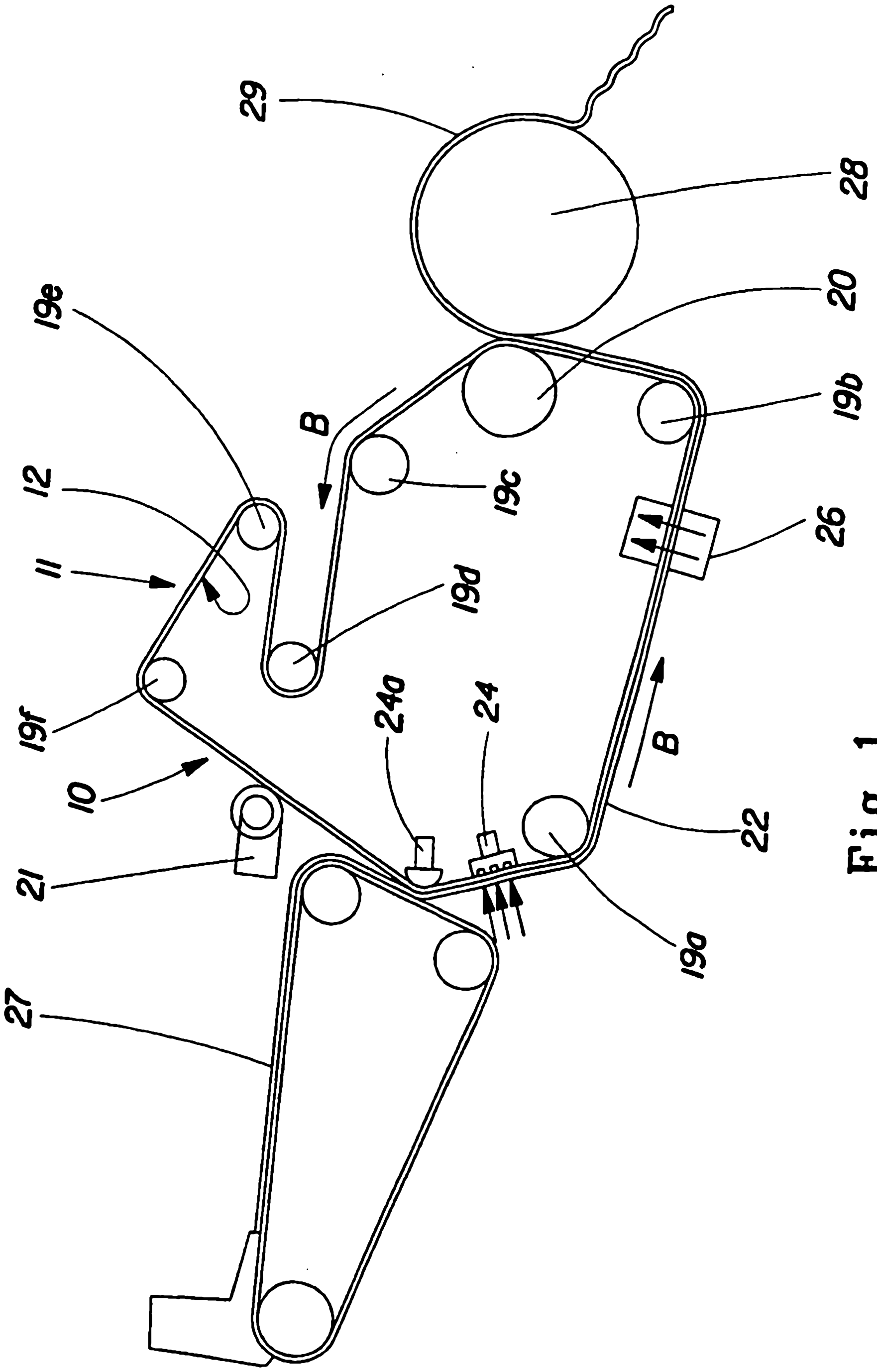


Fig. 1

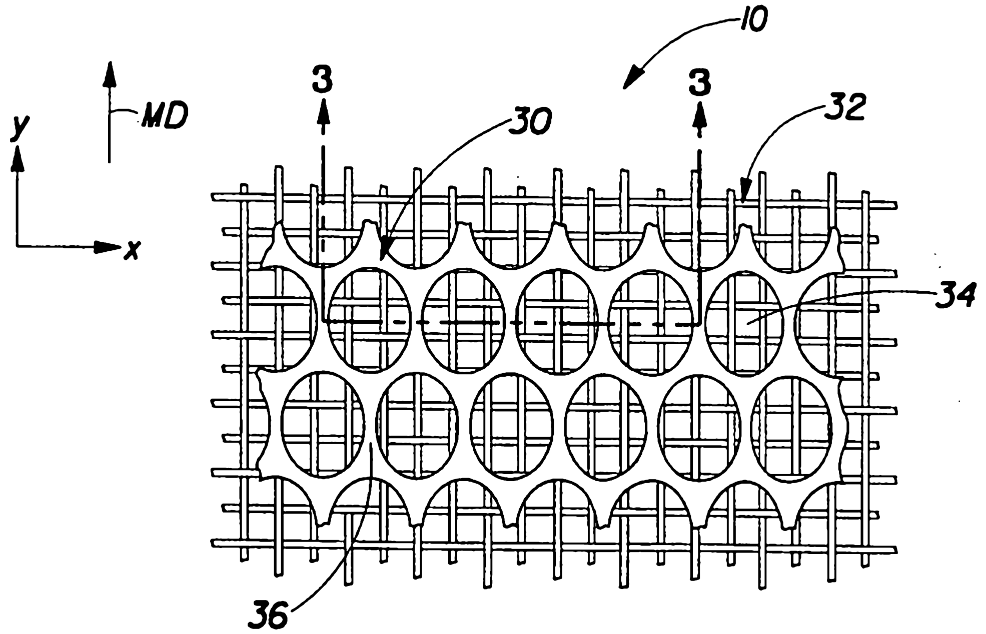


Fig. 2

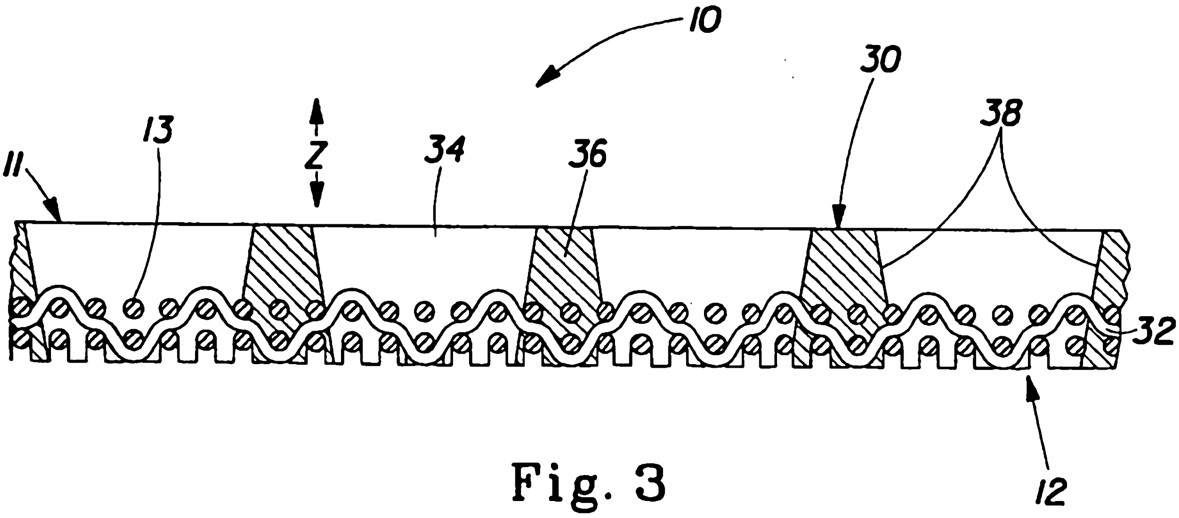


Fig. 3

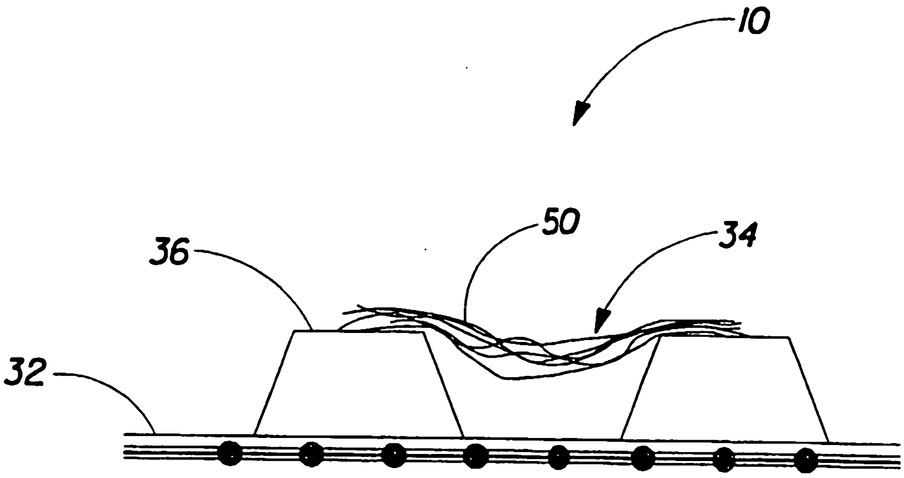


Fig. 4

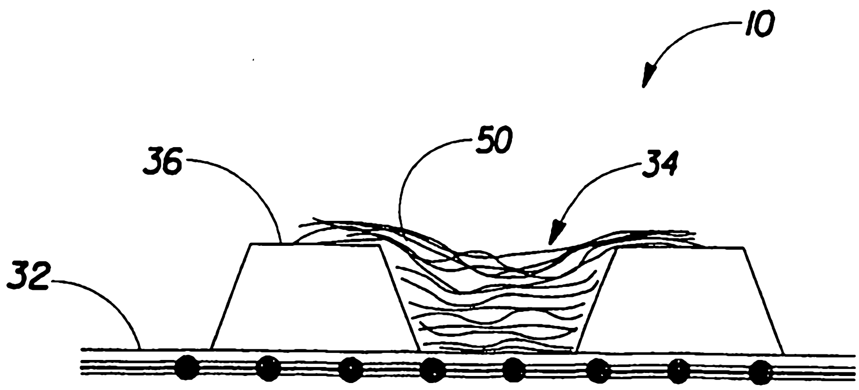


Fig. 5

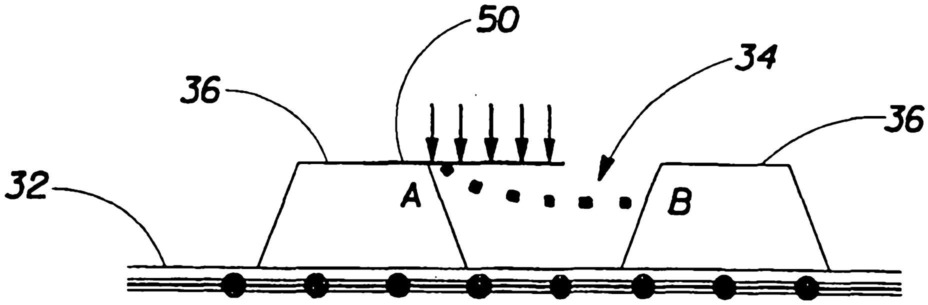


Fig. 6

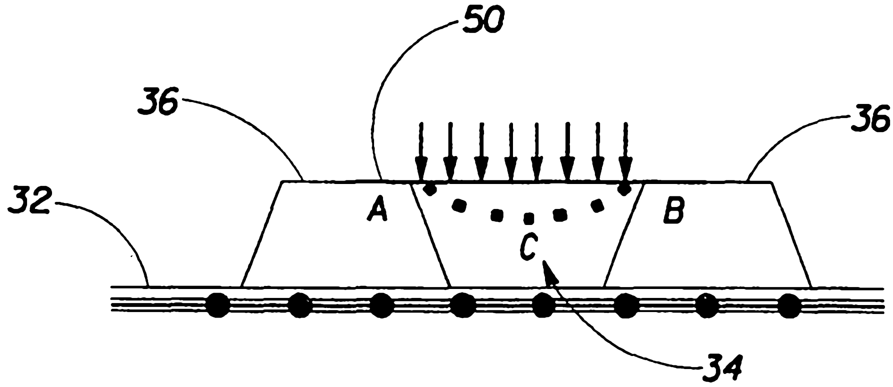


Fig. 7

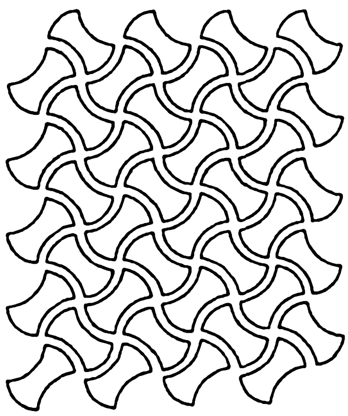


Fig. 8a

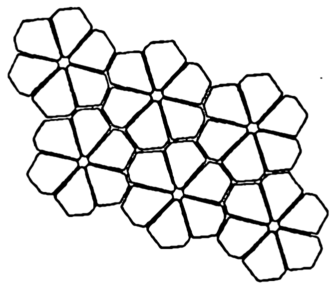


Fig. 8b

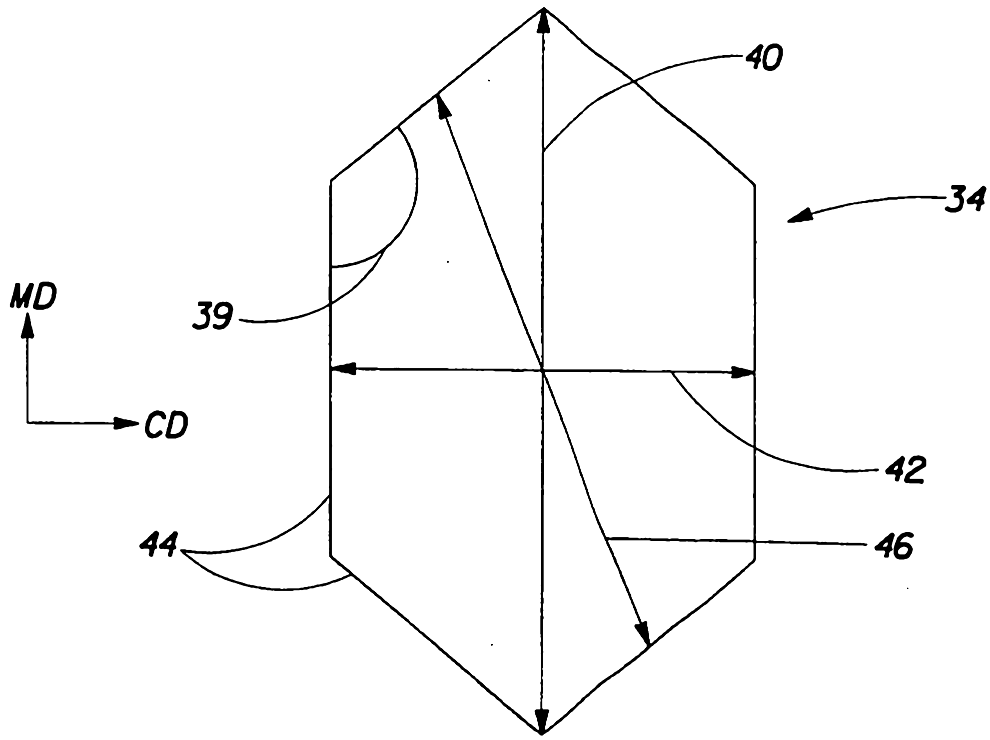


Fig. 9

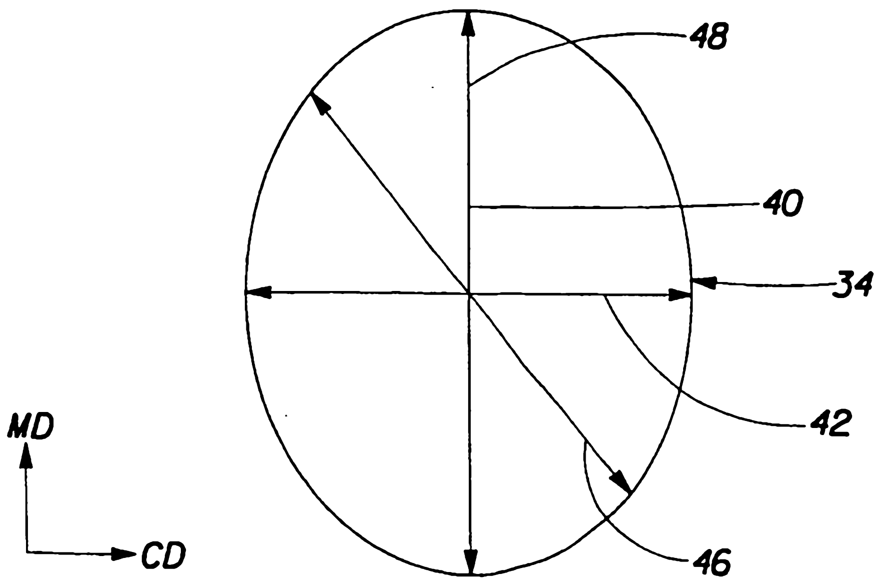


Fig. 10

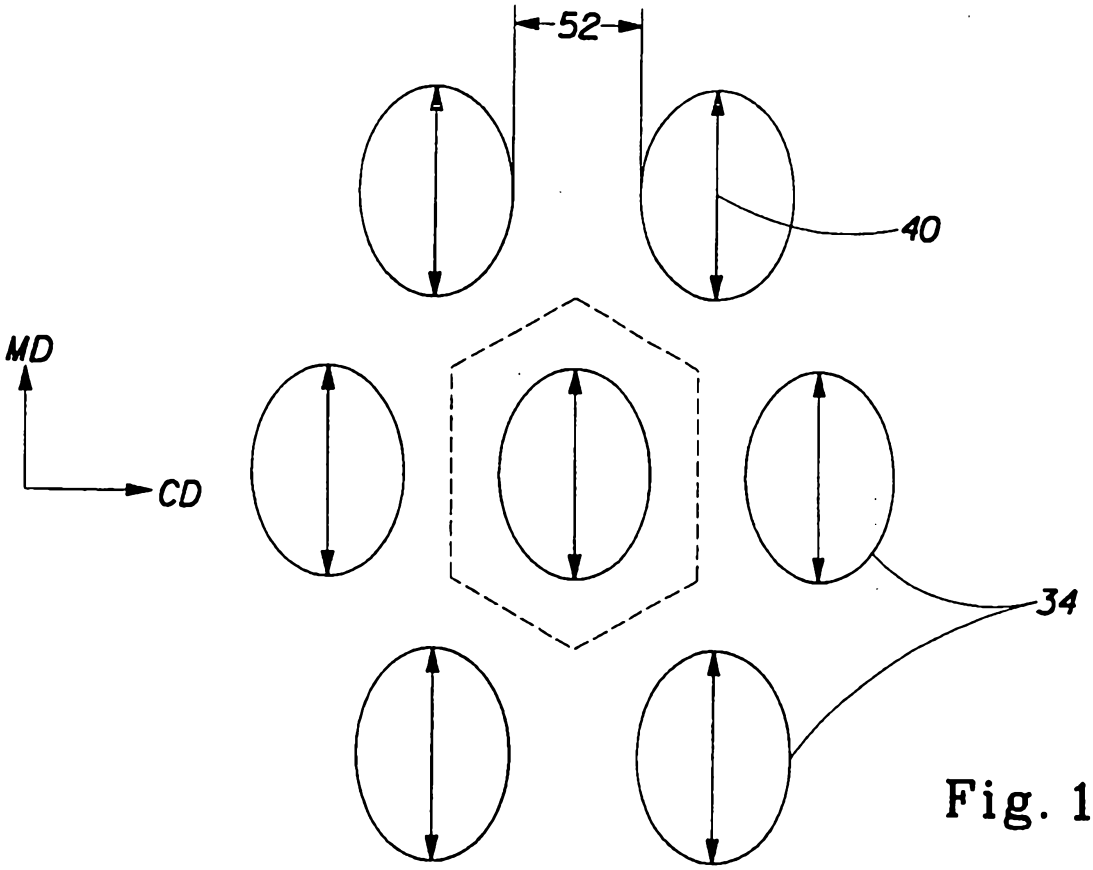


Fig. 11

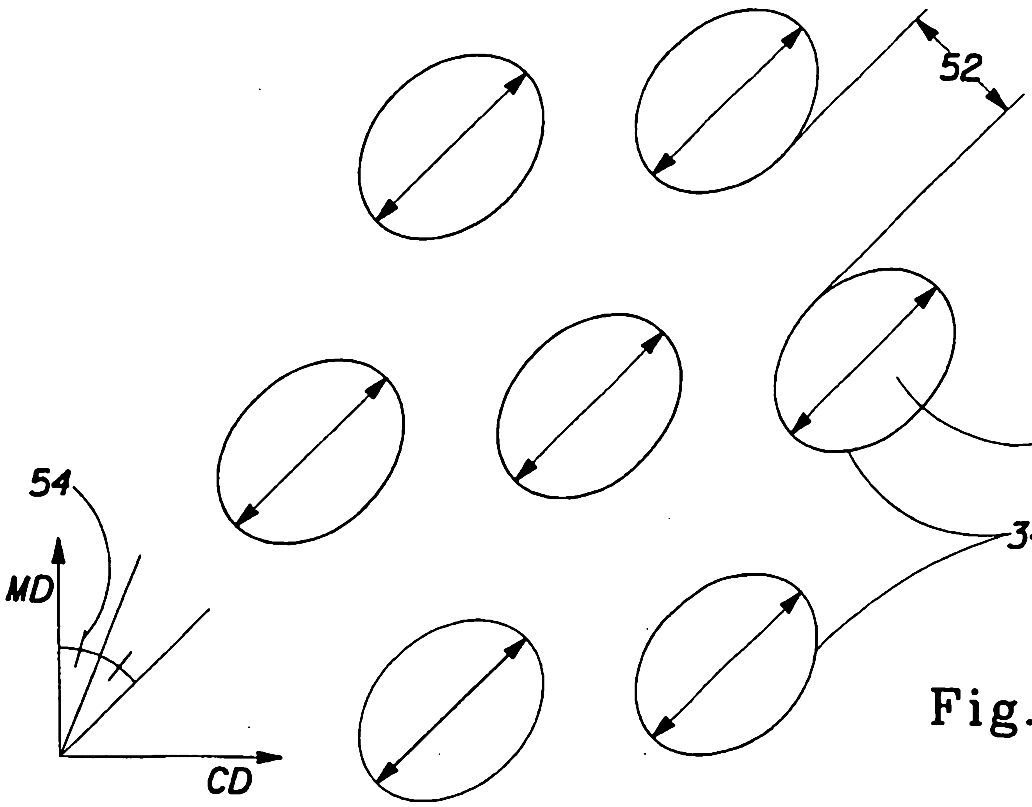


Fig. 12

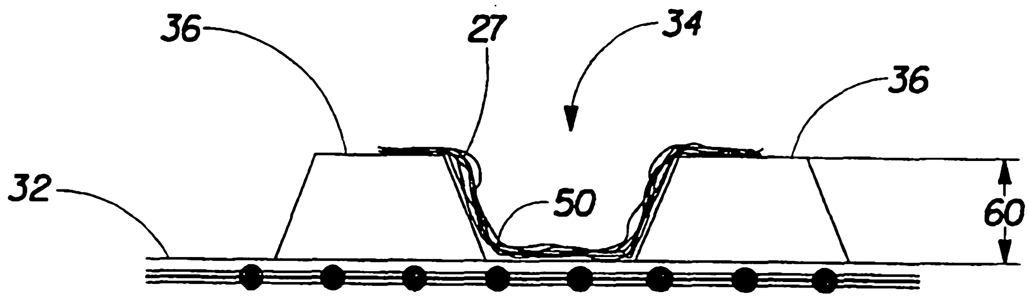


Fig. 13

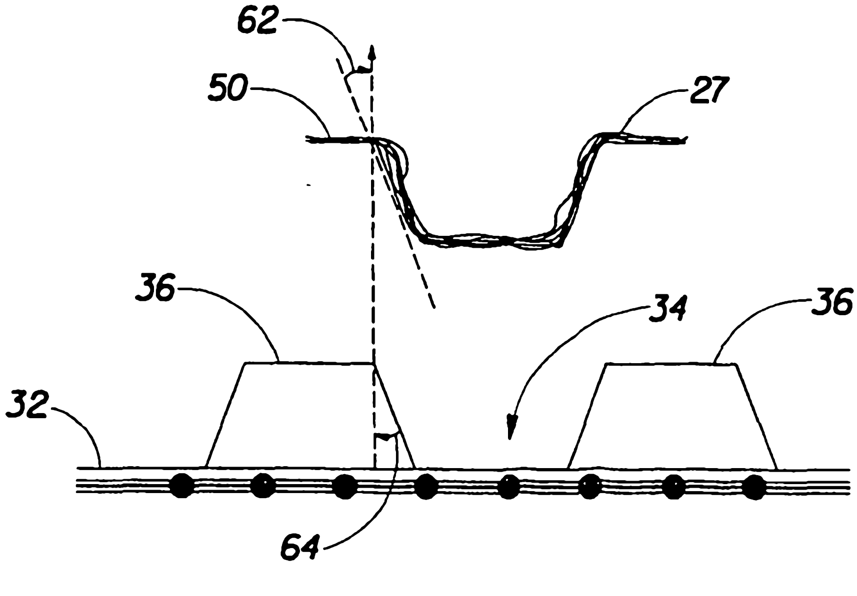


Fig. 14

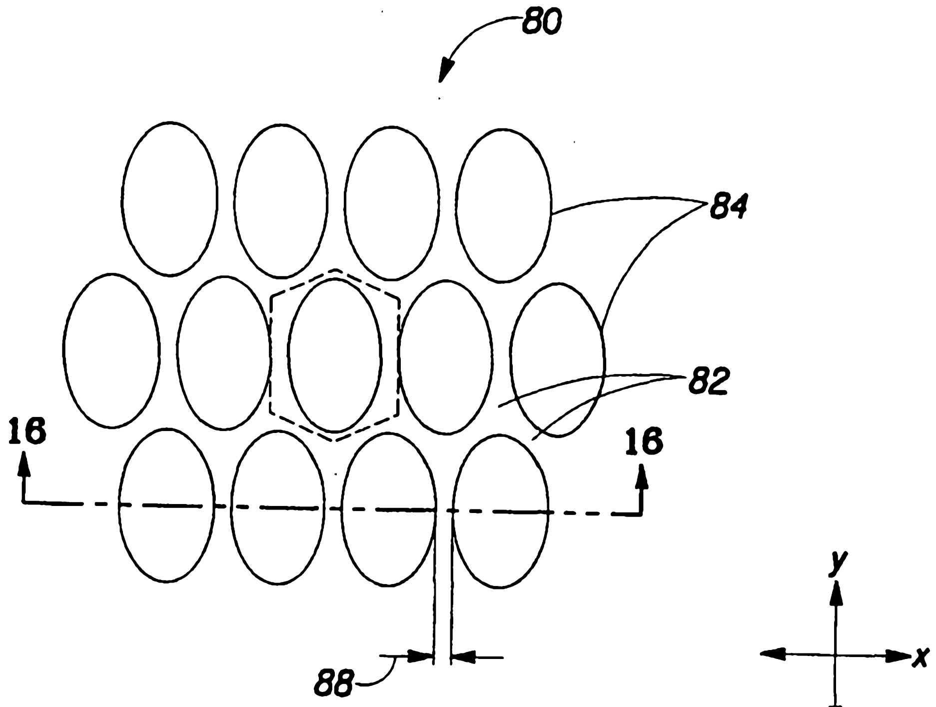


Fig. 15

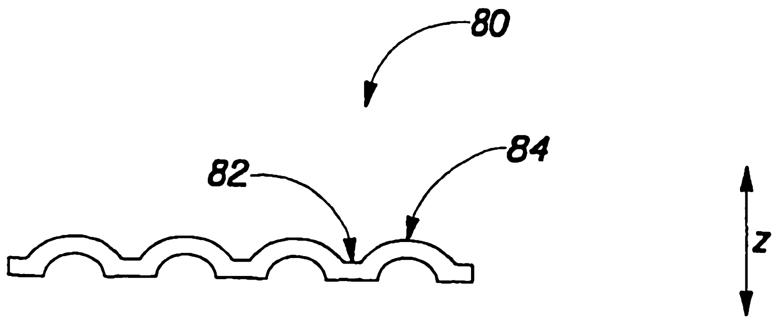


Fig. 16