

**METHODS FOR BONDING HIGHLY FLEXIBLE SUBSTRATE
TO A CARRIER AND PRODUCT FORMED THEREBY**

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 62/106417 filed on January 22, 2015, the content of which is relied upon and incorporated herein by reference in its entirety.

BACKGROUND

[0002] The present disclosure relates to methods and apparatus for processing a flexible substrate, such as a highly flexible substrate, using so-called sheet manufacturing techniques, which are designed for thicker and stiffer substrates.

[0003] Sheet manufacturing techniques are typically employed to process respective substrates (e.g., glass sheets) by conveying the respective sheets from a source, through any number of processing steps (heating, scoring, trimming, cutting, etc.), to a destination. The conveyance of the respective sheets may involve a number of elements that cooperate to move the respective substrates from station to station, preferably without degrading any desirable characteristics of the substrates. For example, typical transport mechanisms may include any number of noncontact support members, contact support members, rollers, lateral guides, etc., to guide the substrates through the system from the source, through each process station, and finally to the destination. The non-contact support members may include air bearings, fluid bar(s), low friction surface(s), etc. Non-contact support elements may include a combination of positive and negative fluid pressure streams in order to “float” the substrates during conveyance. Contact support elements may include rollers to stabilize the substrates during transport through the system.

[0004] The aforementioned transport mechanisms for sheet manufacturing systems are typically designed for relatively thick substrates, such as thicknesses that exhibit a sufficient stiffness to retain suitable mechanical dimensionality, material integrity, and/or other properties despite the forces that may be inflicted on the substrates during conveyance and processing through the manufacturing system. For example, typical sheet manufacturing techniques for cover glass used in liquid crystal displays (or other similar applications)

typically require that the glass substrates exhibit a relatively high stiffness, such as may be the case when the substrates have thicknesses on the order of about 0.5 mm or greater.

[0005] Use of these sheet manufacturing techniques may become problematic, however, when substrates having significantly lower stiffness (e.g., highly flexible glass substrates) are processed.

[0006] At least some of the problems that might arise using sheet manufacturing techniques on highly flexible substrates may be overcome by designing specialized processing equipment for conveying and processing such substrates. Such design, however, would require significant non-recurring expense in terms of time and resources, as well as rendering existing (and possibly fully paid for) production equipment obsolete. For example, when processing highly flexible substrates, the conventional sheet manufacturing techniques may be discarded in favor of a “roll-to-roll” conveyance and processing equipment. In principle, such a substitution might lead to lower manufacturing costs in the long term; however, the non-recurring expense to design and implement a new roll-to-roll system for highly flexible substrate material would be very significant, and possibly require innovation to process certain types of flexible substrates.

[0007] Accordingly, there are needs in the art for new methods and apparatus for modifying flexible substrates such that they may be processed using sheet processing techniques.

SUMMARY

[0008] For purposes of discussion, the disclosure herein may often refer to methodologies and apparatus involving substrates formed from glass; however, skilled artisans will realize that the methodologies and apparatus herein apply to substrates of numerous kinds, including glass substrates, crystalline substrates, single crystal substrates, glass ceramic substrates, polymer substrates, etc.

[0009] For example, one type of flexible substrate material is referred to as Corning® Willow® Glass, which is a glass material suitable for many purposes. The relatively thin material (about 0.1 mm thick, which is approximately the thickness of a sheet of paper), combined with the strength and flexibility of the glass material, support applications from the ordinary to the very highly sophisticated, such as wrapping a display element around a device or structure. Corning® Willow® Glass may be used for very thin backplanes, color filters,

etc., for both organic light emitting diodes (OLED) and liquid crystal displays (LCD), such as may be used in high performance, portable devices (e.g., smart phones, tablets, and notebook computers). Corning® Willow® Glass may also be used for producing electronic components, such as touch sensors, seals for OLED displays and other moisture and oxygen sensitive technologies. Corning® Willow® Glass may be on the order of about 100 μm (micrometers or microns) to 200 μm thick, and highly flexible, having glass characteristics including: a density of about 2.3 – 2.5 g/cc, Young's Modulus of about 70 – 80 GPa, Poisson Ratio of about 0.20 – 0.25, and minimum bend radius of about 185 – 370 mm.

[0010] If respective substrates of Corning® Willow® Glass were processed using typical sheet manufacturing techniques, the thinness and flexibility of the material would likely result in degradation of the material characteristics of the glass, critical failure of the glass, and/or interruption or damage to the sheet processing equipment.

[0011] Embodiments of the present disclosure seek to address the problems of processing flexible substrates, such as thin and flexible glass substrates, in existing sheet manufacturing systems (which are designed for thicker, stiffer substrates). In particular, the methods and apparatus seek to provide for temporarily bonding the flexible substrate to a thicker and/or stiffer carrier substrate, which presents the flexible substrate as having stiffer mechanical characteristics while being processed in the sheet processing system. After processing, the temporary bond is released and the flexible substrate is subject to further manufacturing, processing, or delivery to a customer.

[0011a] In an aspect of the present invention, there is provided a method comprising:
providing a carrier substrate formed from a sheet of material, the carrier substrate having a length dimension in an X-axis, a width dimension in a Y-axis, and a thickness dimension in a Z-axis, where the X-axis and Y-axis define an X-Y plane;

providing a flexible substrate formed from a sheet of material, the flexible substrate having a length dimension in the X-axis, a width dimension in the Y-axis, and a thickness dimension in the Z-axis, and wherein at least one of: (i) the flexible substrate has a thickness of from about 50 μm to about 300 μm , and (ii) the flexible substrate has at least one of: a density of about 2.3 – 2.5 g/cc, a Young's Modulus of about 70 – 80 GPa; a Poisson Ratio of about 0.20 – 0.25, and a minimum bend radius of about 185 – 370 mm;

at least one of stressing and straining the carrier substrate to induce a curvature out of the X-Y plane in a first direction along the Z-axis;

locating the flexible substrate over the carrier substrate, while maintaining the at least one of stressing and straining of the carrier substrate; and

inducing a bond between the flexible substrate and the carrier substrate, wherein the bond initiates at a start area and, thereafter, a bond front propagates the bond from the start area until the flexible substrate is bonded to the carrier substrate,

wherein the induced curvature out of the X-Y plane in the first direction along the Z-axis in the carrier substrate is maintained prior to, and at least partially during, the bonding process such that characteristics of the bond front tend to cause the bonded flexible substrate and the carrier substrate to curve out of the X-Y plane in a second direction along the Z-axis, opposite to the first direction.

[0011b] There is also disclosed an apparatus comprising:

a carrier substrate formed from a sheet of material, the carrier substrate having a length dimension in an X-axis, a width dimension in a Y-axis, and a thickness dimension in a Z-axis, where the X-axis and Y-axis define an X-Y plane; and

a flexible substrate formed from a sheet of material, which is bonded to the carrier substrate, the flexible substrate having a length dimension in the X-axis, a width dimension in the Y-axis, and a thickness dimension in the Z-axis, wherein at least one of: (i) a flexibility of the flexible substrate is substantially more flexible than a flexibility of the carrier substrate, and (ii) the thickness of the flexible substrate is substantially less than a thickness of the carrier substrate,

wherein an amount of deformation out of the X-Y plane after bonding is less than at least one of: (i) about 200 μm ; (ii) about 100 μm ; (iii) about 75 μm ; and (iii) about 50 μm .

[0012] Other aspects, features, and advantages will be apparent to one skilled in the art from the description herein taken in conjunction with the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

[0013] For the purposes of illustration, there are forms shown in the drawings that are presently preferred, it being understood, however, that the embodiments disclosed and described herein are not limited to the precise arrangements and instrumentalities shown.

[0014] FIG. 1 is a perspective view, schematic illustration of a process in which a flexible substrate is bonded to a carrier substrate in preparation for processing the flexible substrate in a conventional sheet manufacturing system;

[0015] FIG. 2 is a side view, schematic illustration of the flexible substrate bonded to the carrier substrate for processing the flexible substrate in the conventional sheet manufacturing system;

[0016] FIG. 3 is a perspective view, schematic illustration of a first sequence in which the flexible substrate may be bonded to the carrier substrate, which results in a dome-shaped out-of-plane deformation of the bonded structure;

[0017] FIG. 4 is a graphical illustration of a quantitative measure of the out-of-plane deformation of the bonded structure of FIG. 3;

[0018] FIG. 5 is a perspective view, schematic illustration of a second sequence in which the flexible substrate may be bonded to the carrier substrate, which results in a cylindrically-shaped out-of-plane deformation of the bonded structure;

[0019] FIG. 6 is a graphical illustration of a quantitative measure of the out-of-plane deformation of the bonded structure of FIG. 5;

[0020] FIGS. 7A, 7B, and 7C are schematic illustrations of tools that may be employed to initiate a start area and a bond front that characterizes the bonding process of FIG. 5;

[0021] FIG. 8 is a forming machine that is configured to induce an out-of-plane curvature in the carrier substrate prior to bonding in order to counteract the propensity for the out-of-plane deformation that would otherwise occur in the bonded structure;

[0022] FIG. 9 is a graphical illustration of a quantitative measure of the out-of-plane deformation of the bonded structure resulting from the induced out-of-plane curvature in the carrier substrate of FIG. 8;

[0023] FIGS. 10A and 10B is a schematic illustration of a thermal process of bonding the flexible substrate to the carrier substrate in order to counteract the propensity for the out-of-plane deformation that would otherwise occur in the bonded structure.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0024] For purposes of discussion, the embodiments discussed below refer to the processing of a flexible substrate formed from glass, which is a preferred material. It is noted, however, that the embodiments may employ different materials to implement the

flexible substrate, such as crystalline substrates, single crystal substrates, glass ceramic substrates, polymer substrates, etc.

[0025] Reference is now made to FIG. 1, which is a perspective view, schematic illustration of a process in which a flexible substrate 102 is temporarily bonded to a carrier substrate 104 in preparation for processing the flexible substrate 102 in a conventional sheet manufacturing system. As mentioned previously, the rationale for bonding the flexible substrate 102 to the thicker and/or stiffer carrier substrate 104 is to present the flexible substrate 102 as if it had stiffer mechanical characteristics while being processed in the sheet processing system that is designed for handling stiffer substrates than the flexible substrate 102.

[0026] With reference to FIG. 2, a schematic illustration of the resulting bonded structure 100 (the flexible substrate 102 atop the carrier substrate 104) is shown. In this regard, the carrier substrate 104 may be formed from a sheet of material, such as a glass material, where the carrier substrate 104 has a length dimension in an X-axis, a width dimension in a Y-axis, and a thickness dimension in a Z-axis (within a Cartesian Coordinate System). Notably, the X-axis and Y-axis define an X-Y plane, which may be referred to herein as being in-plane and/or defining an in-plane reference. Similarly, the flexible substrate 102 is formed from a sheet of material, which may also be a glass material, where the flexible substrate 102 has a length dimension in the X-axis, a width dimension in the Y-axis, and a thickness dimension in the Z-axis. As previously discussed, the flexible substrate 102 exhibits at least one of: (i) a flexibility that is substantially more flexible than a flexibility of the carrier substrate 104, and (ii) a thickness that is substantially less than a thickness of the carrier substrate 104.

[0027] In one or more embodiments, the flexible substrate 102 may be formed from glass and have a thickness of one of: (i) from about 50 μm (microns or micrometers) to about 300 μm , and (ii) from about 100 μm to about 200 μm . In accordance with one or more further embodiments, the flexible substrate 102 may have at least one of: a density of about 2.3 – 2.5 g/cc, a Young's Modulus of about 70 – 80 GPa; a Poisson Ratio of about 0.20 – 0.25, and a minimum bend radius of about 185 – 370 mm.

[0028] Similarly, in one or more embodiments, the carrier substrate 104 may be formed from glass; however, the carrier substrate 104 preferably has a thickness of one of at least from about 400 to about 1000 μm , notably thicker than the flexible substrate 102.

[0029] Although further details regarding the bond between the flexible substrate 102 and the carrier substrate 104 will be presented later herein, it is preferred that the bond is temporary, and employed primarily for the purpose of processing the flexible substrate 102 in a conventional sheet manufacturing system. After such processing, the temporary bond may be undone and the flexible substrate 102 may be separated from the carrier substrate 104 for further processing and/or application outside the conventional sheet manufacturing system.

[0030] Any number of mechanisms and/or processes for achieving the bond (temporary or otherwise) between the flexible substrate 102 and the carrier substrate 104 may be employed, so long as the bond parameters and characteristics discussed later herein are also considered and compensated for. By way of example, one skilled in the art may employ and/or modify one or more of the bonding processes disclosed in the following patent applications in achieving the conditions disclosed herein: U.S. Provisional Patent Application No. 61/736,887, filed on December 13, 2012; U.S. Patent Application No. 14/047,506, filed on October 7, 2013; U.S. Provisional Patent Application No. 61/931,924 filed on January 27, 2014; U.S. Provisional Patent Application No. 61/931,912, filed on January 27, 2014; U.S. Provisional Patent Application No. 61/931,927 filed on January 27, 2014; and U.S. Provisional Patent Application No. 61/977,364 filed on April 9, 2014, the entire disclosures of which are hereby incorporated by reference.

[0031] In order to more fully appreciate the advantages of the methods and apparatus disclosed herein, a detailed discussion of some bonding properties and phenomena will be now be presented with reference to FIGS. 3 and 4. FIG. 3 is a perspective, schematic illustration of an example of a sequence in which the flexible substrate 102 may be bonded to the carrier substrate 104, which results in a substantially dome-shaped, out-of-plane deformation of the bonded structure 100. FIG. 4 is a graphical illustration of a quantitative measure of the out-of-plane deformation of the bonded structure 100 of FIG. 3.

[0032] Again, for purposes of discussion, prior to, and at least partially during, the bonding process, the flexible substrate 102 and the carrier substrate 104 are characterized by respective length dimensions in the X-axis, respective width dimensions in the Y-axis, and respective thickness dimensions in the Z-axis. The X-axis and Y-axis thereby define an X-Y plane, which is an in-plane reference (against which a flatness of the bonded structure 100 is compared, for example in FIG. 4).

[0033] With specific reference to FIG. 3, the bonding process may include locating the flexible substrate 102 over the carrier substrate 104 and then inducing the bond. More particularly, when the flexible substrate 102 is located over the carrier substrate 104 there will typically be some atmospheric gas (such as air) that maintains some relatively small separation between the substrates. In order to initiate the bond, a start area may be established by a localized urging of the flexible substrate 102 and the carrier substrate 104 together, such as via a mechanical pressing force. In the illustrated example, a single point and/or generally circular area may be established as the start area 20 by way of a focused pressure of the flexible substrate 102 toward, and into contact with, the carrier substrate 104, which is illustrated by the arrow 22.

[0034] Skilled artisans will appreciate that one or more other bonding criteria may also be brought into play along with inducing the start area (see the aforementioned U.S. patent application disclosures). In so doing, the induced bond at the start area 20 will propagate in accordance with a bond front 24. In the case of the illustrated start area 20 (i.e., the single point and/or generally circular area), the bond front 24 will include radially directed vectors extending away from the start area 20 in all directions in the X-Y plane. The bond front 24 will continue to expand radially outwardly in the X-Y plane until it reaches an edge of the substrates, at which time the flexible substrate 102 is bonded to the carrier substrate 104.

[0035] Through experimentation, it has been discovered that the aforementioned (radially extending) bond front 24 will cause the bonded structure 100 to deform out-of-plane (i.e., out of a reference plane defined by the Y-Y plane). In particular, the radially extending bond front 24 results in a generally dome-shaped, out-of-plane curvature in the Z-axis, which is shown in the example as being in the downward direction along the Z-axis. Stated another way, without some compensating mechanism, the mere bonding of the flexible substrate 102 to the carrier substrate 104 will produce an undesirable out-of-plane curvature, which if left unmodified may produce further undesirable effects in the down-stream processes of the sheet manufacturing system. Indeed, it is generally understood that the conventional sheet manufacturing system works best when the incoming substrates to be processed (in this case the bonded structures 100) are relatively flat.

[0036] The bonded structure 100 in FIG. 3, however, is not generally flat. Indeed, with reference to FIG. 4, a graphical illustration of a quantitative measure of the out-of-plane

deformation of an example of the bonded structure 100 of FIG. 3 is shown. In connection with the laboratory experimentation, the Z-axis of the graph in FIG. 4 is measured in μm , and the X-axis and Y-axis are measured in mm. The out-of-plane, generally dome-shaped curvature is on the order of 225 – 300 μm at a maximum. Such curvature may not be acceptable in conventional sheet manufacturing systems and/or may result in defective intermediate products, which are unsuitable for commercial applications. As will be discussed in more detail later herein, compensation of such undesirable bonding phenomena may be achieved in accordance with embodiments herein.

[0037] Another example of the out-of-plane curvature resulting from bonding the flexible substrate 102 to the carrier substrate 104 will now be presented with reference to FIGS. 5 and 6. FIG. 5 is a perspective, schematic illustration of an example of an alternative sequence in which the flexible substrate 102 may be bonded to the carrier substrate 104, which results in a substantially cylindrically-shaped, out-of-plane deformation of the bonded structure 100. FIG. 6 is a graphical illustration of a quantitative measure of the out-of-plane deformation of the bonded structure 100 of FIG. 5 obtained through experimentation.

[0038] With specific reference to FIG. 5, the bonding process may again include locating the flexible substrate 102 over the carrier substrate 104 and then inducing the bond. In order to initiate the bond, the start area is again established by a localized urging of the flexible substrate 102 and the carrier substrate 104 together, such as via a mechanical pressing force. In the illustrated example, as compared with the previous example of FIG. 3 however, a generally linearly extending start area 30 is established by way of a linearly extending focused pressure of the flexible substrate 102 toward, and into contact with, the carrier substrate 104. Mechanisms for producing the linearly extending pressure and resultant linearly directed and extending start area 30 will be discussed in more detail later herein.

[0039] In the case of the illustrated linearly directed and extending start area 30, the bond front 34 will include linearly directed vectors extending transversely away from the elongate direction of the start area 30, in the X-Y plane. For example, the start area 30 may extend substantially linearly along a line parallel to the Y-axis (such as along adjacent edges of the respective substrates 102, 104 shown at the right of FIG. 5). As a result, the bond front 34 has been found to include vectors that are spaced substantially linearly along a line parallel to the Y-axis (such as the line 30), and propagate away from the start area 30 in a

direction transverse to the Y-axis (e.g., in a direction parallel to the X-axis, perpendicular to the Y-axis). The bond front 34 will continue to expand linearly away from the start area 30 in the X-Y plane until it reaches the end of the substrates, at which time the flexible substrate 102 is bonded to the carrier substrate 104.

[0040] Skilled artisans will appreciate that a variation of the process shown in FIG. 5 and discussed immediately above includes initiating the start area 30 in an intermediate location along the X-axis, e.g., somewhere between the adjacent edges of the respective substrates 102, 104. In such case, the bond front 34 will again include vectors that are spaced substantially linearly along a line parallel to the Y-axis (such as the line 30), and again will propagate away from the start area 30 in a direction transverse thereto. Notably, however, the bond front 34 would include two components, one component of vectors extending linearly (and transversely) away from the start area 30 in one direction (e.g., leftward in FIG. 5), and another component of vectors extending linearly (and transversely) away from the start area 30 in another, opposite direction (e.g., rightward in FIG. 5). Both components of the bond front 34 will continue to expand linearly away from the start area 30 in the X-Y plane until they reach an edge of the substrates, at which time the flexible substrate 102 is bonded to the carrier substrate 104.

[0041] Through experimentation, it has been discovered that the aforementioned (linearly extending) bond front 34 will also cause the bonded structure 100 to deform out-of-plane (i.e., out of a reference plane defined by the X-Y plane). In particular, the linearly extending bond front 34 results in a generally cylindrical-shaped, out-of-plane curvature in the Z-axis, which is shown in the example as being in the downward direction along the Z-axis. Again, without some compensating mechanism, the mere bonding of the flexible substrate 102 to the carrier substrate 104 will produce an undesirable out-of-plane curvature, which if left unmodified may produce further undesirable effects in the down-stream processes of the conventional sheet manufacturing system. Again, the bonded structure 100 in FIG. 5 is not generally flat. Indeed, with reference to FIG. 6, laboratory experimentation reveals that the out-of-plane, generally cylindrical-shaped curvature is on the order of 200 – 250 μm at a maximum.

[0042] As mentioned previously, skilled artisans will appreciate that there are a number of mechanisms that may be employed for producing the linearly extending pressure and resultant linearly directed and extending start area 30. For example, with reference to

FIG. 7A, a leaf-spring arrangement 32-1 may be employed, which includes a relatively rigid frame member 40 and a relatively flexible spring element 42. The flexible spring element 42 is rotationally coupled to the frame member via respective hinged couplings 44-1, 44-2 to produce a leaf-spring deflection element. In operation, the frame member 40 and spring element 42 are oriented parallel to the desired linear start area 30, such as above the flexible substrate 102. A downwardly directed force is then applied to the frame member 40 such that the flexible spring element 42 urges the flexible substrate 102 against the carrier substrate 104 along a line, thereby producing the desired start area 30.

[0043] In an alternative example, with reference to FIG. 7B, a rocker-type arrangement 32-2 may be employed, which includes a relatively rigid structure 50 having a curved blade portion 52, which may be referred to as a rocker press. In operation, the structure 50 and the blade portion 52 are oriented parallel to the desired linear start area 30, such as above the flexible substrate 102. A downwardly directed and rocking force is then applied to the structure 50 such that the curved blade portion 52 urges the flexible substrate 102 against the carrier substrate 104 along a line, thereby producing the desired start area 30.

[0044] In a further alternative example, with reference to FIG. 7C, a multi-point linear press arrangement 32-3 may be employed, which includes a relatively rigid frame member 60 and a plurality of pressing elements 62 resiliently engaged thereto. The pressing elements may themselves be resilient and/or may include some bias mechanism permitting individual ones, or groups of, the pressing elements 62 to give when pressed. In operation, the frame member 60 and the linear array of pressing elements 62 are oriented parallel to the desired linear start area 30, such as above the flexible substrate 102. A downwardly directed force is then applied to the frame member 60 such that the pressing elements 62 urge the flexible substrate 102 against the carrier substrate 104 along a line, thereby producing the desired start area 30.

[0045] Skilled artisans will appreciate that there are a number of non-contact mechanisms that may be employed for producing the linearly extending pressure and resultant linearly directed and extending start area 30. In a further alternative example, not shown, the non-contact means may include one or more of: (i) one or more air jets; (ii) one or more air bearings; and (iii) one or more ultrasonic bearings.

[0046] As mentioned previously, compensation of the dome-shaped and/or the cylindrical-shaped out-of-plane deformations due to undesirable bonding phenomena may be

achieved in accordance with embodiments herein. In general, such compensation may be achieved by manipulating the carrier substrate 104 prior to the bonding operation. For example, the process may include at least one of stressing and straining the carrier substrate 104 to induce a curvature out of the X-Y plane in a direction along the Z-axis that counteracts the induced curvature out of the X-Y plane that would occur via the bond front propagation phenomena. Thus, for example, if the bond front propagation phenomena tends to induce curvature out of the X-Y plane in a direction characterized as shown in FIGS. 3 and 5 (e.g., in a downward direction or negative Z-axis direction), then the general compensation methodology involves at least one of stressing and straining the carrier substrate 104 to induce a curvature out of the X-Y plane in an opposite direction (e.g., upward or positive Z-axis direction).

[0047] After such induced curvature in the carrier substrate 104 is achieved, the bonding process may include locating the flexible substrate 102 over the carrier substrate 104, while maintaining the at least one of stressing and straining of the carrier substrate 104. Next, the start area is established and the bond front propagation ensues until the flexible substrate 102 and the carrier substrate are bonded together. A degree of the induced curvature in the carrier substrate 104 prior to, and at least partially during, the bonding process is controlled such that the characteristics of the curvature out of the X-Y plane due to the bond front are substantially cancelled (or at least mitigated).

[0048] Taking the cylindrical-shaped out-of-plane deformation case first, reference is now made to FIG. 8, which is a schematic illustration of a forming machine that is configured to counteract the propensity for the out-of-plane deformation that would otherwise occur in the bonded structure 100. The forming machine includes a base 70 and a biasing surface 72, spaced apart from the base 70. The biasing surface 72 may be curved with respect to the base 70 by way of one or more actuators. A first actuator 74 may be located generally in a central region (central along the X-axis) of the forming machine. The first actuator 74 may include a biasing member 76, such as a rod or the like, that extends generally parallel to the Y-axis and operates to urge the biasing surface 72 upwardly in the positive Z-axis direction. An adjustment mechanism 78 operates to provide control in an offset position of the biasing member 76 from the base 70, and control of an amount of biasing action by the biasing member 76 against the biasing surface 72. An optional second actuator 82 may operate to move a lateral edge of the biasing surface 72 parallel with the base 70 and closer to, or further

from, the biasing member 76, thereby also providing some adjustable amount of biasing action by the biasing member 76 against the biasing surface 72. One or both of the actuators 74, 82 may be computer controlled. Such actuation results in an adjustable amount of cylindrical-shaped out-of-plane curvature of the biasing surface 72 in a direction opposite to the direction of the curvature shown in FIG. 5.

[0049] In operation, the carrier substrate 104 may be placed on the biasing surface 72 forming machine such that manipulation of the carrier substrate 104 may be achieved prior to the bonding operation. In particular the biasing surface 72 induces mechanical stress and/or strain in the carrier substrate 104 to induce a cylindrical-shaped out-of-plane curvature (out of the X-Y plane) in a direction along the Z-axis that counteracts the induced curvature out of the X-Y plane that would occur via the bond front propagation phenomena. For example, the of stressing and/or straining via the biasing surface 72 may be characterized as mechanically bending the carrier substrate 104 about an axis that is spaced away from the X-Y plane in the Z-axis direction, and that is parallel to the Y-axis, to induce the curvature. In FIG. 8, such axis 90 is located below and parallel to the biasing member 76, thereby defining a radius of curvature 92 of the biasing surface 72 and the carrier substrate 104, such that the curvature out of the X-Y plane is a positive direction in the Z-axis (e.g., an upward direction as illustrated).

[0050] After such induced curvature in the carrier substrate 104 is achieved, the bonding process may include locating the flexible substrate 102 over the carrier substrate 104, while maintaining the at least one of stressing and straining of the carrier substrate 104. Next, the start area 30 is established using one of the aforementioned mechanisms or some alternative mechanism. By way of example, the start area 30 may extend substantially linearly along a line parallel to the Y-axis such that the bond front 34 extends (i.e., vectors are spaced) substantially linearly along a line parallel to the Y-axis. Thus, the bond front 34 propagates away from the start area 30 and in a direction transverse to the Y-axis (e.g., the bond front propagation is parallel to the X-axis). Thereafter, the linear bond front 34 propagation continues until the flexible substrate 102 and the carrier substrate 104 are bonded together. The induced curvature in the carrier substrate 104 prior to, and at least partially during, the bonding process by the biasing surface 72 is controlled such that the characteristics of the curvature out of the X-Y plane due to the bond front 34 are mitigated.

[0051] FIG. 9 is a graphical illustration of a quantitative measure of the out-of-plane deformation of the bonded structure 100 resulting from use of the aforementioned compensation methodology and/or apparatus. In particular, laboratory experimentation reveals that the out-of-plane curvature of the compensated bonded structure 100 is less than at least one of: (i) about 200 μm ; (ii) about 100 μm ; (iii) about 75 μm ; and (iii) about 50 μm . By comparison, the out-of-plane curvature of the non-compensated bonded structure 100 graphically illustrated in FIG. 6 exhibited curvatures on the order of 200 – 250 μm at a maximum, and some experimental results show that the out-of-plane curvature of the non-compensated bonded structure 100 may be on the order of 300 – 400 μm .

[0052] Skilled artisans will appreciate that the dome-shaped out-of-plane deformation case may be addressed by providing a mechanism (e.g., a mechanical mechanism) for at least one of stressing and straining the carrier substrate 104 into a dome shape that counteracts the dome-shaped, out-of-plane deformation that occurs due to the radially extending bond front 24 propagation of FIG. 3. In other words, prior to bonding the flexible substrate 102 to the carrier substrate 104, a mechanical mechanism may be employed to urge the carrier substrate 104 into a dome-shaped curvature out of the X-Y plane in a Z-axis direction opposite to that shown in FIG. 3. Thereafter, the bond area 20 (single point or localized diameter) may be induced and the radially extending bond front 24 may propagate until the flexible substrate 102 is bonded to the carrier substrate 104. It is contemplated that the induced dome-shaped curvature in the carrier substrate 104 prior to, and at least partially during, the bonding process by the mechanical mechanism is controlled such that the characteristics of the curvature out of the X-Y plane due to the bond front 24 are mitigated.

[0053] In an alternative embodiment, the at least one of stressing and straining the carrier substrate 104 into a dome-shape prior to bonding may be achieved thermally. In this regard, reference is made to FIGS. 10A and 10B, which are schematic illustrations of a thermal process of bonding the flexible substrate 102 to the carrier substrate 104 in order to counteract the propensity for the out-of-plane deformation that would otherwise occur in the bonded structure 100. The thermal process includes heating at least one of the flexible substrate 102 and the carrier substrate 104 to differing temperatures T1, T2 prior to initiating the bond (FIG. 10A). Next, the flexible substrate 102 is located over the carrier substrate 104 (FIG. 10B) and the radially extending bond front 24 is induced in accordance with the aforementioned procedures. Notably, the differing temperatures T1, T2 are substantially

maintained at least partially during the inducement of the bond and propagation of the radially extending bond front 24. Thereafter, the flexible substrate 102 and the carrier substrate 104 are permitted to reach thermal equilibrium after the bond is achieved. Again, it is contemplated that the induced stress and/or strain in the carrier substrate due to the thermal process prior to, and at least partially during, the bonding process is controlled such that the characteristics of the curvature out of the X-Y plane due to the bond front 24 are mitigated.

[0054] Although the disclosure herein has been described with reference to particular embodiments, it is to be understood that these embodiments are merely illustrative of the principles and applications of the embodiments herein. It is therefore to be understood that numerous modifications may be made to the illustrative embodiments and that other arrangements may be devised without departing from the spirit and scope of the present application. The various described features may be combined in any and all combinations as, for example, according to the following aspects of the disclosure.

[0055] According to a first aspect, there is provided a method comprising:

- providing a carrier substrate formed from a sheet of material, the carrier substrate having a length dimension in an X-axis, a width dimension in a Y-axis, and a thickness dimension in a Z-axis, where the X-axis and Y-axis define an X-Y plane;

- providing a flexible substrate formed from a sheet of material, the flexible substrate having a length dimension in the X-axis, a width dimension in the Y-axis, and a thickness dimension in the Z-axis;

- at least one of stressing and straining the carrier substrate to induce a curvature out of the X-Y plane in a first direction along the Z-axis;

- locating the flexible substrate over the carrier substrate, while maintaining the at least one of stressing and straining of the carrier substrate; and

- inducing a bond between the flexible substrate and the carrier substrate, wherein the bond initiates at a start area and, thereafter, a bond front propagates the bond from the start area until the flexible substrate is bonded to the carrier substrate,

- wherein characteristics of the bond front tend to cause the bonded flexible substrate and the carrier substrate to curve out of the X-Y plane in a second direction along the Z-axis, opposite to the first direction.

[0056] According to a second aspect, there is provided the method of aspect 1, wherein the at least one of stressing and straining includes mechanically bending the carrier substrate cylindrically.

[0057] According to a third aspect, there is provided the method of aspect 2, wherein:
the at least one of stressing and straining includes mechanically bending the carrier substrate about an axis that is spaced away from the X-Y plane in the Z-axis direction, and that is parallel to the Y-axis, to induce the curvature; and

the curvature is characterized by a curvature radius from the axis to the carrier substrate such that the curvature out of the X-Y plane is in the first direction along the Z-axis.

[0058] According to a fourth aspect, there is provided the method of aspect 3, wherein:

the start area extends substantially linearly along a line parallel to the Y-axis;

the bond front extends substantially linearly along a line parallel to the Y-axis;

the bond front propagates away from the start area and in a direction transverse to the Y-axis.

[0059] According to a fifth aspect, there is provided the method of aspect 4, wherein the direction of the bond front propagation is parallel to the X-axis.

[0060] According to a sixth aspect, there is provided the method of aspect 3, wherein the start area is induced by pressing the flexible substrate toward, and into contact with, the carrier substrate along a linearly extending zone.

[0061] According to a seventh aspect, there is provided the method of aspect 6, wherein the linear extending zone is achieved by pressing against the flexible substrate via at least one of: (i) a leaf-spring deflection element; (ii) a rocker press; (iii) a multi-point linear press; (iv) one or more air jets; (v) one or more air bearings; and (vi) one or more ultrasonic bearings.

[0062] According to an eighth aspect, there is provided the method of aspect 1, wherein the at least one of stressing and straining includes mechanically bending the carrier substrate into a dome shape.

[0063] According to a ninth aspect, there is provided the method of aspect 8, wherein:
the at least one of stressing and straining includes heating at least one of the flexible substrate and the carrier substrate to differing temperatures prior to and during the inducement of the bond and propagation of the bond front; and

permitting the flexible substrate and the carrier substrate to reach thermal equilibrium after the bond is achieved.

[0064] According to a tenth aspect, there is provided the method of aspect 9, wherein:
the start area is substantially a circular area or central point; and
the bond front extends substantially radially outwardly from the start area.

[0065] According to an eleventh aspect, there is provided the method of aspect 10, wherein the start area is induced by pressing the flexible substrate toward, and into contact with, the carrier substrate at the substantially central point.

[0066] According to a twelfth aspect, there is provided the method of any one of aspects 1-11, wherein the flexible substrate is formed from glass.

[0067] According to a thirteenth aspect, there is provided the method any one of aspects 1-12, wherein the flexible substrate has a thickness of one of: (i) from about 50 μm to about 300 μm , and (ii) from about 100 μm to about 200 μm .

[0068] According to a fourteenth aspect, there is provided the method of any one of aspects 1-13, wherein the flexible substrate has at least one of: a density of about 2.3 – 2.5 g/cc, a Young's Modulus of about 70 – 80 GPa; a Poisson Ratio of about 0.20 – 0.25, and a minimum bend radius of about 185 – 370 mm.

[0069] According to a fifteenth aspect, there is provided the method any one of aspects 1-14, wherein the carrier substrate is formed from glass.

[0070] According to a sixteenth aspect, there is provided the method any one of aspects 1-15, wherein the carrier substrate has a thickness of one of at least about 400 to about 1000 μm .

[0071] According to a seventeenth aspect, there is provided the method any one of aspects 1-16, wherein an amount of deformation out of the X-Y plane after bonding is less than at least one of: (i) about 200 μm ; (ii) about 100 μm ; (iii) about 75 μm ; and (iii) about 50 μm .

[0072] According to an eighteenth aspect, there is provided the method any one of aspects 1-17, wherein at least one of: (i) a flexibility of the flexible substrate is substantially more flexible than a flexibility of the carrier substrate, and (ii) the thickness of the flexible substrate is substantially less than a thickness of the carrier substrate

[0073] According to a nineteenth aspect, there is provided a flexible substrate bonded to a carrier substrate formed in accordance with a process, comprising the steps of:

providing the carrier substrate formed from a sheet of material, the carrier substrate having a length dimension in an X-axis, a width dimension in a Y-axis, and a thickness dimension in a Z-axis, where the X-axis and Y-axis define an X-Y plane;

providing the flexible substrate formed from a sheet of material, the flexible substrate having a length dimension in the X-axis, a width dimension in the Y-axis, and a thickness dimension in the Z-axis, wherein at least one of: (i) a flexibility of the flexible substrate is substantially more flexible than a flexibility of the carrier substrate, and (ii) the thickness of the flexible substrate is substantially less than a thickness of the carrier substrate;

at least one of stressing and straining the carrier substrate to induce a curvature out of the X-Y plane in a first direction along the Z-axis;

locating the flexible substrate over the carrier substrate, while maintaining the at least one of stressing and straining of the carrier substrate; and

inducing a bond between the flexible substrate and the carrier substrate, wherein the bond initiates at a start area and, thereafter, a bond front propagates the bond from the start area until the flexible substrate is bonded to the carrier substrate, wherein:

characteristics of the bond front tend to cause the bonded flexible substrate and the carrier substrate to curve out of the X-Y plane in a second direction along the Z-axis, opposite to the first direction; and

an amount of deformation out of the X-Y plane after bonding is less than at least one of: (i) about 200 μm ; (ii) about 100 μm ; (iii) about 75 μm ; and (iii) about 50 μm .

[0074] According to a twentieth aspect, there is provided an apparatus, comprising:

a carrier substrate formed from a sheet of material, the carrier substrate having a length dimension in an X-axis, a width dimension in a Y-axis, and a thickness dimension in a Z-axis, where the X-axis and Y-axis define an X-Y plane; and

a flexible substrate formed from a sheet of material, which is bonded to the carrier substrate, the flexible substrate having a length dimension in the X-axis, a width dimension in the Y-axis, and a thickness dimension in the Z-axis, wherein at least one of: (i) a flexibility of the flexible substrate is substantially more flexible than a flexibility of the carrier substrate, and (ii) the thickness of the flexible substrate is substantially less than a thickness of the carrier substrate,

wherein an amount of deformation out of the X-Y plane after bonding is less than at least one of: (i) about 200 μm ; (ii) about 100 μm ; (iii) about 75 μm ; and (iii) about 50 μm .

[0075] According to a twenty-first aspect, there is provided the apparatus of aspect 20, wherein the flexible substrate has a thickness of one of: (i) from about 50 μm to about 300 μm , and (ii) from about 100 μm to about 200 μm .

[0076] According to a twenty-second aspect, there is provided the apparatus of aspect 20 or aspect 21, wherein the flexible substrate has at least one of: a density of about 2.3 – 2.5 g/cc, a Young's Modulus of about 70 – 80 GPa; a Poisson Ratio of about 0.20 – 0.25, and a minimum bend radius of about 185 – 370 mm.

[0077] According to a twenty-third aspect, there is provided the apparatus of any one of aspects 20-22, wherein the carrier substrate is formed from glass.

[0078] According to a twenty-fourth aspect, there is provided the apparatus of any one of aspects 20-23, wherein the carrier substrate has a thickness of one of at least about 400 to about 1000 μm .

CLAIMS:

1. A method comprising:

providing a carrier substrate formed from a sheet of material, the carrier substrate having a length dimension in an X-axis, a width dimension in a Y-axis, and a thickness dimension in a Z-axis, where the X-axis and Y-axis define an X-Y plane;

providing a flexible substrate formed from a sheet of material, the flexible substrate having a length dimension in the X-axis, a width dimension in the Y-axis, and a thickness dimension in the Z-axis, and wherein at least one of: (i) the flexible substrate has a thickness of from about 50 μm to about 300 μm , and (ii) the flexible substrate has at least one of: a density of about 2.3 – 2.5 g/cc, a Young's Modulus of about 70 – 80 GPa; a Poisson Ratio of about 0.20 – 0.25, and a minimum bend radius of about 185 – 370 mm;

at least one of stressing and straining the carrier substrate to induce a curvature out of the X-Y plane in a first direction along the Z-axis;

locating the flexible substrate over the carrier substrate, while maintaining the at least one of stressing and straining of the carrier substrate; and

inducing a bond between the flexible substrate and the carrier substrate, wherein the bond initiates at a start area and, thereafter, a bond front propagates the bond from the start area until the flexible substrate is bonded to the carrier substrate,

wherein the induced curvature out of the X-Y plane in the first direction along the Z-axis in the carrier substrate is maintained prior to, and at least partially during, the bonding process such that characteristics of the bond front tend to cause the bonded flexible substrate and the carrier substrate to curve out of the X-Y plane in a second direction along the Z-axis, opposite to the first direction.

2. The method of claim 1, wherein the at least one of stressing and straining includes mechanically bending the carrier substrate cylindrically.

3. The method of claim 2, wherein:

the at least one of stressing and straining includes mechanically bending the carrier substrate about an axis that is spaced away from the X-Y plane in the Z-axis direction, and that is parallel to the Y-axis, to induce the curvature;

the curvature is characterized by a curvature radius from the axis to the carrier substrate such that the curvature out of the X-Y plane is in the first direction along the Z-axis;

the start area extends substantially linearly along a line parallel to the Y-axis;

the bond front extends substantially linearly along a line parallel to the Y-axis; and

the bond front propagates away from the start area and in a direction transverse to the Y-axis.

4. The method of claim 3, wherein the start area is induced by pressing the flexible substrate toward, and into contact with, the carrier substrate along a linearly extending zone, and further wherein the linear extending zone is achieved by pressing against the flexible substrate via at least one of: (i) a leaf-spring deflection element; (ii) a rocker press; (iii) a multi-point linear press; (iv) one or more air jets; (v) one or more air bearings; and (vi) one or more ultrasonic bearings.

5. The method of claim 1, wherein the at least one of stressing and straining includes mechanically bending the carrier substrate into a dome shape.

6. The method of claim 5, wherein:
the at least one of stressing and straining includes heating at least one of the flexible substrate and the carrier substrate to differing temperatures prior to and during the inducement of the bond and propagation of the bond front; and
permitting the flexible substrate and the carrier substrate to reach thermal equilibrium after the bond is achieved.

7. The method of claim 6, wherein:
the start area is substantially a circular area or central point; and the bond front extends substantially radially outwardly from the start area.

8. The method of any one of claims 1 to 7, wherein the flexible substrate exhibits at least one of: (i) a flexibility that is more flexible than a flexibility of the carrier substrate, and (ii) a thickness that is less than a thickness of the carrier substrate.