

(57) Abstract: A glass article and associated brush polishing methods are described. The glass article includes a polished edge extending between a first major surface and a second major surface. The polished edge exhibits at least one of: (a) an Ra surface roughness that is greater than or equal to 1 nm and less than or equal to 20nm; (b) a root mean squared surface roughness that is greater than or equal to 1 nm and less than or equal to 30 nm; and (c) a peak to valley surface roughness that is greater than or equal to 10 nm and less than or equal to 50 nm. The glass article is strengthened prior to brush polishing such that a majority of the polished edge is not under compressive stress. The brush polishing process is performed such that a first layer of compressive stress extends to the polished edge.

EDGE PROFILE FOR STRENGTHENED GLASS ARTICLES AND ASSOCIATED METHODS AND APPARATUSES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority of U.S. Provisional Application Serial No. 63/524007, filed on June 29, 2023, the content of which is relied upon and incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] This application relates to edge profiles for strengthened glass articles and associated methods. More particularly, the present disclosure pertains to glass articles that are edge polished after strengthening and exhibit a high degree of mechanical strength.

BACKGROUND

[0002] Demand is strong and increasing for high edge strength thin glass display substrates of complex form factors. Where demand for such substrates conventionally resided in the consumer electronics space (e.g., handheld electronics), it is now growing rapidly in new spaces such as automotive and even advanced optics applications. Much like their handheld electronics counterparts (cell phones and tablets), new thin glass substrates of complex shapes are often made from thin glass to satisfy consumer requirements for overall weight (as in the case of automotive glazing products), surface cleanliness (as in the case of electrochromic windows in the architectural glass space), and functionality (as in the case of automotive interior products) while maintaining high mechanical edge strength.

[0003] Conventional singulation of thin substrates, such as glass substrates, having relatively high strength often includes a plurality of mechanical edge grinding and polishing steps. Typically, edges may be formed using course grinding materials, which may introduce subsurface damage on substrate edges. The edges may further be subject to a progression of grinding steps with a plurality of grinding wheels having decreasing abrasive sizes in order to reduce the subsurface damage introduced by the initial edge forming. The edge grinding steps may be used to reduce subsurface damage introduced by initial grinding or other edge forming processes. Such mechanical grinding may damage the edges of the substrate, leaving cuts, chips, and other flaws that lower mechanical edge strength of the substrate. To remove damage caused by the mechanical grinding and thus improve edge strength, the edges are typically

polished with a progression of polishing wheels. Such conventional edge forming and finishing processes may be time consuming, capital inefficient, and expensive, often comprising one of the most expensive and time-consuming operations of the substrate formation

[0004] Thus, there is a need in the art for an improved edge forming and finishing process suitable for manufacturing high strength, complex form, thin substrates.

SUMMARY

[0005] The following presents a simplified summary of one or more embodiments of the present disclosure in order to provide a basic understanding of such embodiments. This summary is not an extensive overview of all contemplated embodiments and is intended to neither identify key or critical elements of all embodiments, nor delineate the scope of any or all embodiments.

[0006] An aspect (1) of the present disclosure pertains to a glass article comprising: a first major surface; a second major surface disposed opposite the first major surface; and a polished edge extending between the first major surface and the second major surface, wherein: the polished edge comprises at least one of: (a) an Ra surface roughness that is greater than or equal to 1 nm and less than or equal to 20nm; (b) a root mean squared surface roughness that is greater than or equal to 1 nm and less than or equal to 30 nm; and (c) a peak to valley surface roughness that is greater than or equal to 10 nm and less than or equal to 50 nm, the glass article is chemically strengthened such that the glass article comprises a first layer of compressive stress extending from the first major surface to a first depth of compression (DOC₁) and a second layer of compressive stress extending from the second major surface to a second depth of compression (DOC₂), wherein a majority of the polished edge is not under compressive stress, and at least one of the first layer of compressive stress and the second layer of compressive stress extends to the polished edge.

[0007] An aspect (2) of the present disclosure pertains to a glass article according to the aspect (1), wherein: the polished edge comprises a plurality of brush marks arranged thereon in a substantially parallel configuration, the brush marks imparted by a brush polishing process.

[0008] An aspect (3) of the present disclosure pertains to a glass article according to any of the aspects (1)-(2), wherein a plurality of the glass articles with the same composition, thickness, and chemical strengthening exhibit a Weibull distribution with a B10 value that is greater than or equal to 500 MPa, when tested for mechanical edge strength using a four-point bend test in accordance with ASTM C158-02.

[0009] An aspect (4) of the present disclosure pertains to a glass article according to any of the aspects (1)-(3), wherein the polished edge exhibits all of (a), (b), and (c).

[0010] An aspect (5) of the present disclosure pertains to a glass article according to any of the aspects (1)-(4), wherein: the glass article comprises a maximum thickness (T) measured between major surfaces of the glass article, and the polished edge comprises a length that is greater than $T - \text{DOC}_1 - \text{DOC}_2$.

[0011] An aspect (6) of the present disclosure pertains to a glass article according to any of the aspects (1)-(5), wherein, in a cross section of the glass article taken in a direction perpendicular to the polished edge and the first major surface, the first major surface comprises a first peripheral region where material of the glass article was removed from the first major surface during a brush polishing process, wherein the first peripheral region comprises a width measured in a direction perpendicular to the polished edge that is less than or equal to 200 μm .

[0012] An aspect (7) of the present disclosure pertains to a glass article according to the aspect (6), wherein: the first peripheral region comprises a curved region extending inward from the polished edge, wherein, within the cross-section, the polished edge transitions to the curved region at a boundary of an outer surface of the glass article, and at the boundary, the outer surface exhibits a minimum radius of curvature that is greater than or equal to twice a maximum thickness of the glass article, as measured between the first major surface and the second major surface.

[0013] An aspect (8) of the present disclosure pertains to a glass article according to the aspect (7), wherein the curved region comprises: a width taken in the direction perpendicular to the polished edge that is less than or equal to $2 * \text{DOC}_1$, and a depth taken in a direction perpendicular to the first major surface at a geometric center of the first major surface, the depth being less than or equal to $0.5 * \text{DOC}_1$.

[0014] An aspect (9) of the present disclosure pertains to a glass article according to any of the aspects (6)-(8), wherein, in the cross section, the second major surface comprises a second peripheral region where material of the glass article was removed from the second major surface during the brush polishing process.

[0015] An aspect (10) of the present disclosure pertains to a glass article according to the aspect (9), wherein the first and second peripheral regions comprise different shapes such that the glass article comprises asymmetrical chamfers.

[0016] An aspect (11) of the present disclosure pertains to a glass article according to any of the aspects (1)-(10), further comprising an anti-reflective coating disposed on the first major surface, the anti-reflective coating comprising alternating layers of higher and lower

refractive index materials, wherein a periphery of the first major surface exhibits a golden hue when viewed from normal incidence and illuminated with a diffuse D65 illuminate simulating ambient lighting conditions.

[0017] An aspect (12) of the present disclosure pertains to a glass article according to any of the aspects (1)-(11), wherein the first and second major surfaces are devoid of brush marks associated with a brush polishing process performed on the polished edge.

[0018] An aspect (13) of the present disclosure pertains to a glass article according to the aspect (12), wherein the first and second major surfaces comprise slurry flow lines, the slurry flow lines comprising a maximum width that is less than 3 μm .

[0019] An aspect (14) of the present disclosure pertains to a glass article according to any of the aspects (1)-(13), further comprising an ink layer disposed on the second major surface, the ink layer comprising an outer boundary offset from the polished edge by a distance of less than 160 μm measured perpendicular to the polished edge.

[0020] An aspect (15) of the present disclosure pertains to a glass article according to the aspect (14), wherein the outer boundary comprises slurry flow lines from a flow of a polishing slurry associated with a brush polishing process, the slurry flow lines extending substantially parallel to the outer boundary.

[0021] An aspect (16) of the present disclosure pertains to a glass article comprising: a first major surface; a second major surface disposed opposite the first major surface; and a polished edge extending between the first major surface and the second major surface, wherein: the polished edge comprises at least one of: (a) an R_a surface roughness that is greater than or equal to 1 nm and less than or equal to 20 nm; (b) a root mean squared surface roughness that is greater than or equal to 1 nm and less than or equal to 30 nm; and (c) a peak to valley surface roughness that is greater than or equal to 10 nm and less than or equal to 50 nm, the glass article is chemically strengthened such that the glass article comprises at least a first layer of compressive stress extending from the first major surface to a first depth of compression (DOC_1), in a cross section of the glass article taken in a direction perpendicular to the polished edge and the first major surface, the first major surface comprises a first peripheral region where material of the glass article was removed from the first major surface during a polishing process, wherein the first peripheral region comprises a depth measured in a direction perpendicular to the first major surface at a geometric center of the first major surface, wherein the depth is less than or equal to $0.5 \cdot \text{DOC}_1$ such that a portion of the polished edge is under compressive stress, wherein a majority of the polished edge is not under compressive stress.

[0022] An aspect (17) of the present disclosure pertains to a glass article according to the aspect (16), wherein the first peripheral region comprises a width measured in a direction perpendicular to the polished edge that is less than or equal to 200 μm .

[0023] An aspect (18) of the present disclosure pertains to a glass article according to the aspect (17), wherein the width is less than or equal to $2 \cdot \text{DOC}_1$.

[0024] An aspect (19) of the present disclosure pertains to a glass article according to any of the aspects (16)-(18), wherein: the first peripheral region comprises a curved region extending inward from the polished edge, wherein, within the cross-section, the polished edge transitions to the curved region at a boundary of an outer surface of the glass article, and at the boundary, the outer surface exhibits a minimum radius of curvature that is greater than or equal to twice a maximum thickness of the glass article, as measured between the first major surface and the second major surface.

[0025] An aspect (20) of the present disclosure pertains to a glass article according to any of the aspects (16)-(19), wherein, in the cross section, the second major surface comprises a second peripheral region where material of the glass article was removed from the second major surface during the brush polishing process.

[0026] An aspect (21) of the present disclosure pertains to a glass article according to the aspect (20), wherein the first and second peripheral regions comprise different shapes such that the glass article comprises asymmetrical chamfers.

[0027] An aspect (22) of the present disclosure pertains to a glass article according to any of the aspects (16)-(21), further comprising an anti-reflective coating disposed on the first major surface, the anti-reflective coating comprising alternating layers of higher and lower refractive index materials, wherein a periphery of the first major surface exhibits a golden hue when viewed from normal incidence and illuminated with a diffuse D65 illuminate simulating ambient lighting conditions.

[0028] An aspect (23) of the present disclosure pertains to a glass article according to any of the aspects (16)-(22), wherein: the polished edge comprises a plurality of brush marks arranged thereon in a substantially parallel configuration, the brush marks imparted by a brush polishing process.

[0029] An aspect (24) of the present disclosure pertains to a glass article according to the aspect (23), wherein the first and second major surfaces are devoid of the brush marks.

[0030] An aspect (25) of the present disclosure pertains to a glass article according to the aspect (24), wherein the first and second major surfaces comprise slurry flow lines, the slurry flow lines comprising a maximum width that is less than 3 μm .

[0031] An aspect (26) of the present disclosure pertains to a glass article according to any of the aspects (16)-(25), further comprising an ink layer disposed on the second major surface, the ink layer comprising an outer boundary offset from the polished edge by a distance of less than 160 μm measured perpendicular to the polished edge.

[0032] An aspect (27) of the present disclosure pertains to a glass article according to the aspect (26), wherein the outer boundary comprises slurry flow lines from a flow of a polishing slurry associated with a brush polishing process, the slurry flow lines extending substantially parallel to the outer boundary.

[0033] An aspect (28) of the present disclosure pertains to a glass article according to any of the aspects (16)-(27), wherein the polished edge exhibits all of (a), (b), and (c).

[0034] An aspect (29) of the present disclosure pertains to a method of finishing an edge surface of a strengthened glass substrate, the method comprising: arranging the strengthened glass substrate between a first interposer and a second interposer; applying a compressive force to the strengthened glass substrate and interposers; and polishing an edge surface of the strengthened substrate by removing material of the strengthened glass substrate using a rotary brush and a polishing slurry flow, wherein the rotary brush comprises a plurality of brush filaments, wherein contact between the strengthened glass substrate and the rotary brush is concentrated on the edge surface of the substrate, wherein the polishing slurry flow is concentrated on major surfaces of the strengthened glass substrate.

[0035] An aspect (30) of the present disclosure pertains to a method according to the aspect (29), wherein thicknesses of the first and second interposers are greater than a d50 grain size of the polishing slurry flow.

[0036] An aspect (31) of the present disclosure pertains to a method according to any of the aspects (29)-(30), wherein the polishing comprises at least two brush polishing passes.

[0037] An aspect (32) of the present disclosure pertains to a method according to any of the aspects (29)-(31), wherein at most 50 μm of the material of the strengthened glass substrate is removed from the edge surface during the polishing.

[0038] An aspect (33) of the present disclosure pertains to a method according to any of the aspects (29)-(32), wherein the material of the strengthened glass substrate is removed from peripheral portions of major surfaces of the strengthened glass substrate, the peripheral portions having widths that are less than or equal to 200 μm .

[0039] An aspect (34) of the present disclosure pertains to a method according to the aspect (33), wherein, after the polishing, the peripheral portions have depths that are less than

a depth of compression associated with a layer of compressive stress on one of the major surfaces.

[0040] An aspect (35) of the present disclosure pertains to a method according to any of the aspects (29)-(34), wherein each of the brush filaments comprise a filament diameter, wherein the first and second interposers comprise thicknesses that are less than that of the filament diameter to concentrate the contact on the edge surface.

[0041] An aspect (36) of the present disclosure pertains to a method according to the aspect (35), wherein the filament diameter is less than half of the thicknesses of the first and second interposer.

[0042] An aspect (37) of the present disclosure pertains to a method according to any of the aspects (35)-(36), wherein: the plurality of brush filaments comprise a filament length, the brush filament diameter is greater than 0.1 mm, and during the chamfering and polishing, the rotary brush is disposed a distance from the strengthened glass substrate such that at least one third of the filament length of the plurality of brush filaments engage with the edge surface.

[0043] An aspect (38) of the present disclosure pertains to a method according to any of the aspects (29)-(34), wherein: the plurality of brush filaments comprise a filament length and a filament diameter, and one of: (i) during the polishing, the rotary brush is disposed a distance from the strengthened glass substrate such that at less than one fifth of the filament length of the plurality of brush filaments engage with the edge surface, and (ii) the plurality of brush filaments comprise a filament diameter of less than or equal to 0.1 mm.

[0044] An aspect (39) of the present disclosure pertains to a method according to the aspect (38), wherein the filament diameter is less than thicknesses of the first and second interposers.

[0045] An aspect (40) of the present disclosure pertains to a method according to any of the aspects (29)-(39), further comprising disposing an ink layer around a periphery of a major surface of the strengthened glass substrate prior to the polishing, wherein a portion of the ink layer is removed during the polishing by the polishing slurry flow.

[0046] An aspect (41) of the present disclosure pertains to a method according to any of the aspects (29)-(40), further comprising near-net shaping the strengthened glass substrate prior the polishing.

[0047] An aspect (42) of the present disclosure pertains to a method according to the aspect (41), wherein the near-net shaping comprises forming nano-perforations along a contour line in the strengthened glass substrate using a pulsed laser beam and separating the strengthened glass sheet at the contour line via one of thermal separation or self-separation.

[0048] An aspect (43) of the present disclosure pertains to a method according to any of the aspects (29)-(42), wherein the strengthened glass substrate is a chemically strengthened glass substrate.

[0049] While multiple embodiments are disclosed, still other embodiments of the present disclosure will become apparent to those skilled in the art from the following detailed description, which shows and describes illustrative embodiments of the invention. As will be realized, the various embodiments of the present disclosure are capable of modifications in various obvious aspects, all without departing from the spirit and scope of the present disclosure. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

[0050] While the specification concludes with claims particularly pointing out and distinctly claiming the subject matter that is regarded as forming the various embodiments of the present disclosure, it is believed that the invention will be better understood from the following description taken in conjunction with the accompanying Figures, in which:

[0051] FIG. 1A schematically depicts a perspective view of a glass substrate, according to one or more embodiments of the present disclosure;

[0052] FIG. 1B schematically depicts a cross-sectional view of the glass substrate through the line I-I in FIG. 1A, according to one or more embodiments of the present disclosure;

[0053] FIG. 1C schematically depicts a close-up view of the region II of the cross-section depicted in FIG. 1B, according to one or more embodiments of the present disclosure;

[0054] FIG. 2 is a flow diagram of a process for fabricating a glass substrate, according to one or more embodiments of the present disclosure;

[0055] FIG. 3 is a flow diagram of a process for brush polishing a workpiece to provide a glass substrate having the edge profile described herein, according to one or more embodiments of the present disclosure;

[0056] FIGS 4A and 4B schematically depict a rotary brush disposed proximate to a stack of workpieces and interposers for batch brush polishing, according to one or more embodiments of the present disclosure;

[0057] FIG. 5 schematically depicts an apparatus for measuring mechanical edge strength of a glass substrate using a 4-point bend test, according to one or more embodiments of the present disclosure;

[0058] FIG. 6 is an image of a counterexample formed by brush polishing with aggressive material on the major surfaces of a workpiece, according to one or more embodiments of the present disclosure;

[0059] FIG. 7 is an image of a workpiece after near-net shaping via laser singulation proximate to a boundary of a decorative ink layer prior to brush polishing, according to one or more embodiments of the present disclosure;

[0060] FIG. 8 depicts example substrates formed via the brush polishing process described herein with respect to FIG. 3, according to one or more embodiments of the present disclosure;

[0061] FIG. 9 is an image example substrate via the brush polishing process described herein with respect to FIG. 3 including a brush polished decoration boundary, according to one or more embodiments of the present disclosure;

[0062] FIG. 10 is a plot including Weibull distributions of mechanical edge strengths of examples formed via the brush polishing process described herein with respect to FIG. 3 and counterexamples, according to one or more embodiments of the present disclosure;

[0063] FIG. 11A is an image of a workpiece that is a glass-on-glass laminate after near-net shaping and prior to brush polishing, according to one or more embodiments of the present disclosure;

[0064] FIG. 11B is an image of the workpiece depicted in FIG. 11A after brush polishing via the process described herein with respect to FIG. 3, according to one or more embodiments of the present disclosure;

[0065] FIG. 11C is a plot including Weibull distributions of the workpiece depicted in FIGS. 11A and 11B, both before and after polishing, according to one or more embodiments of the present disclosure;

[0066] FIG. 12 is a plot of edge impact resistance results for examples formed using the processes of the present disclosure when tested by a pendulum impact test, according to one or more embodiments of the present disclosure; and

[0067] FIG. 13 is an image of an example formed using the processes of the present disclosure with a decorative ink layer disposed thereon, according to one or more embodiments of the present disclosure.

DESCRIPTION

[0068] The present disclosure relates to processes and devices by which a glass article, which may be near-net shaped by a range of cutting and separation technologies, may be edge

formed and finished to simultaneously remove corresponding damage remaining on the edges in the areas formed by cutting and separation while imposing a desired edge profile and achieving a desired mechanical edge strength. Processes and devices of the present disclosure may be employed to achieve a substrate edge (or “polished edge”) with flaws that are typically less than 2.0 micrometers in length (or depth from the polished edge) and a mechanical edge strength of up to or exceeding 500 MPa (B10 value), with the mechanical edge strength being tested with a four-point bend test in accordance with ASTM C158-02. Polished edges of the articles described herein are generally smooth and devoid of relatively large flaws, exhibiting at least one of: (a) an Ra surface roughness that is greater than or equal to 1 nm and less than or equal to 20 nm; (b) a root mean squared surface roughness that is greater than or equal to 1 nm and less than or equal to 30 nm; and (c) a peak to valley surface roughness that is greater than or equal to 10 nm and less than or equal to 50 nm. In aspects, glass substrates formed using the brush polishing process described herein include all of (a), (b), and (c).

[0069] In aspects, the edge profiles achievable via the process and devices described herein are particularly advantageous when employed on strengthened glass articles such that the polished edge extends between major surfaces of the glass article. Such strengthened glass articles comprise at least a first layer of compressive stress extending from a first major surface to a first depth of compression (DOC₁) within the article and an optional second layer of compressive stress extending from a second major surface to a second depth of compression (DOC₂) within the article. The strengthening can occur through chemical strengthening (e.g., via ion exchange), thermal strengthening, or via use of a glass-on-glass laminate including different glass compositions having differing coefficients of thermal expansion that contact one another when in a molten state to create the layer(s) of compressive stress upon cooling. The processes and devices described herein may be used such that at they produce a polished substrate edge with least a portion of the polished edge being under compressive stress after the polishing removes at least 10 μm of material from the substrate edge (in a direction perpendicular to the substrate edge after singulation and prior to the polishing). That is, at least one layer of compressive stress extends to the polished edge after the brush polishing process is complete. Put differently, a layer of compressive stress on the substrate is subjected to any of the polishing processes described herein (via contact with at least one of a polishing brush, a polishing wheel, or other suitable polishing agent) and still present on the polished edge after the polishing process is conducted to remove at least 10 μm of material from the edge. Such compressive stress is present even though no chemical strengthening is conducted after the polishing. When no chemical strengthening is conducted after the polishing, compressive

stress is only present in a portion of the polished edges (proximate to the major surfaces). This contrasts with certain existing processes, where strengthening is conducted after polishing and the entirety of the edges are under compressive stress.

[0070] In embodiments, in a cross section of the glass article taken in a direction perpendicular to the polished edge and the first major surface, the first major surface comprises a first peripheral region where material of the glass article was removed from the first major surface during a polishing process. In such embodiments, this first peripheral region comprises a depth measured in a direction perpendicular to the first major surface that is less than or equal to $0.5 \cdot \text{DOC}_1$ such that a portion of the polished edge is under compressive stress. The processes and devices of the present disclosure limit material removal from the major surfaces of the glass article during polishing so that a layer of compressive stress, which was present on the entire major surface prior to polishing, still covers the entire major surface after polishing, and is also present on the polished edge. Certain existing polishing processes remove excess material on the major surfaces, eliminating layers of compressive stress from the edges of the part, leading to reduced edge strength. The articles described herein focus material removal at the polished edge and avoid this deficiency.

[0071] The processes and devices described herein address various issues in a manufacturing process which involves near-net shaping of glass substrates after both strengthening (e.g., after ion exchange) and decoration. Some of the benefits associated with such a post strengthening shaping process over other existing process, in which strengthening occurs after near-net shaping, are described in U.S. Patent Application Ser. No. 17/621,049, filed on December 20, 2021, hereby incorporated by reference in its entirety. Particularly, the processes and devices described herein aid in restoring mechanical edge strength of strengthened articles after near-net shaping, without requiring additional processing steps like etching after mechanical polishing (e.g., via passes with a polishing brush or a polishing wheel). Moreover, the processes and devices described herein enable near-net shaping (e.g., singulation) in very close proximity (e.g., within 100 μm , within 70 μm , within 50 μm) of a boundary of a decorative layer (e.g., an ink decoration, such as an organic ink decoration and/or a black matrix ink decoration) disposed on a major surface of the article through application of laser cutting techniques described herein in order to increase glass material utilization. The polishing techniques described herein can be used to improve uniformity (e.g., in terms of flatness) of the boundary of the decorative layer when laser cutting techniques are used in such close proximity to the decoration boundary, resulting in reduced light leakage as compared to articles processed further from the decoration boundary. Such crisp boundaries of the

decoration are smooth, straight, and more visually appealing than those associated with articles processed by other methods. The polished edge may be disposed by a lateral distance (measured parallel to the major surface) that is less than 150 μm (e.g., less than or equal to 125 μm , less than or equal to 100 μm , less than or equal to 70 μm , less than or equal to 60 μm , less than or equal to 50 μm) from the decoration boundary post polishing.

[0072] In aspects, the edge profile described herein is achieved by chamfering and polishing an edge surface of the article after near-net shaping. For example, the chamfering and polishing can remove material of the article using a rotary brush and a polishing slurry flow, with the rotary brush including a plurality of brush filaments. It has been found that concentrating contact of the brush filaments to the substrate edge, rather than on the major surfaces of the article, can aid in achieving the edge profile described herein. Polishing slurry flow is directed to the major surfaces to create peripheral regions of limited material removal thereon. Slurry flow-induced material removal is smaller in scale than brush-induced material removal, and so the peripheral regions of material removal on the major surfaces are limited in size to avoid removing compressive stress layers present at the major surfaces from strengthening. The slurry flow-induced material removal results in curved peripheral regions of the major surfaces after completion of the brush polishing. Such curved peripheral regions may extend to the polished edge and transition to the polished edge via rounded boundaries (e.g., corners) of the article's outer surface. Such rounded boundaries may exhibit relatively high radii of curvature (with the minimum radius of curvature of the boundary being greater than or equal to twice a maximum thickness of the article). As such, directing brush contact away from the major surfaces of the article has the benefit of avoiding relatively sharp corners on the glass article, which tend to concentrate stresses and reduce edge strength.

[0073] In aspects, concentrating contact between the brush filaments of the rotary brush and the edge of the article can be achieved by controlling at least one of spacing of the article from adjacent components in a stack and the engagement between the brush filaments and the article. In embodiments, for example, the article can be arranged in a stack with a plurality of other glass articles, with adjacent ones of the articles being separated from one another by a plurality of interposers. It has been found that the plurality of brush filaments having diameters that are greater than the thicknesses of the interposers can lead to concentrated brush contact at the edge of the article, as there is insufficient space for the brush filaments to get between the articles and contact the major surfaces. In embodiments, irrespective of article spacing in the stack, concentrating brush contact at the edges can be achieved through passive brush engagement. Such passive brush engagement can be achieved by limiting brush engagement

(e.g., to less than one fifth of the length of the plurality of brush filaments) and/or by using brush filaments of relatively small diameter (e.g., less than or equal to 0.1 mm). Polishing slurry flow is directed to interstitial spaces between the articles in the stack by rotating the brushes at a sufficient speed (e.g., at least 100 rpm for a 292 mm diameter cylindrical brush).

[0074] As used herein, the terms “depth of layer” and “DOL” refer to the depth of the compressive layer as determined by surface stress meter (FSM) measurements using commercially available instruments such as the FSM-6000.

[0075] As used herein, the terms “depth of compression” and “DOC” refer to the depth at which the stress within the glass changes from compressive to tensile stress. At the DOC, the stress crosses from a positive (compressive) stress to a negative (tensile) stress and thus has a value of zero.

[0076] As described herein, compressive stress (CS) and central tension (CT) are expressed in terms of megaPascals (MPa), depth of layer (DOL) and depth of compression (DOC) are expressed in terms of microns (μm), where $1\ \mu\text{m}=0.001\ \text{mm}$, and thickness t is expressed herein in terms of millimeters, where $1\ \text{mm}=1000\ \mu\text{m}$, unless otherwise specified.

[0077] With reference to FIGS. 1A, 1B, and 1C, a glass substrate 52 is shown, according to an example embodiment. The glass substrate 52 is formed by the process described herein, and is depicted in a state after a workpiece has been cut from a blank (e.g., larger glass sheet) using any of the near-net shaping techniques described herein, with the workpiece being subsequently polished in accordance with the parameters described herein to form the glass substrate 52. FIG. 1A depicts a perspective view of the glass substrate 52. FIG. 1B depicts a cross-sectional view through the line I-I in FIG. 1A, with the line I-I extending through a geometric center C of the part and in a direction perpendicular to polished edges 58 of the glass substrate. FIG. 1C depicts a close-up view of a portion II of the cross-section depicted in FIG. 1B. As shown, the glass substrate 52 comprises a first major surface 54, a second major surface disposed opposite to the first major surface 56, and a plurality of polished edges 58 extending between the first major surface 54 and the second major surface 56 at the periphery of the glass substrate 52. Substantial (e.g., majority) portions of the first and second major surfaces 54 and 56 can extend parallel to one another. Central portions of the first and second major surfaces may be substantially planar in shape, with such portions of the first major surface 56 that are unmodified during polishing residing in the X-Y plane depicted in FIGS. 1A-1C. The X-Y plane may represent a vertical position of an average surface height of unmodified portions of the first major surface 54 (measured via white light interferometry) when measured relative to a common reference point in the coordinate system represented in

FIGS. 1A-1C. While FIGS. 1A-1C depict a glass substrate 52 with a rectangular peripheral shape, it should be understood that the present disclosure is applicable to glass substrates having any shape and any number of distinct polished edges (e.g., a circular glass substrate may have a single polished edge). Embodiments are also envisioned where the major surfaces of the glass substrate 52 are not planar (e.g., they can be curved).

[0078] As a result of the polishing processes described herein, the first major surface 54 comprises a first peripheral region 60 extending outward from a boundary 62 to the polished edges 58. The boundary 62 represents a series of points on the first major surface 54 where any material of the workpiece was removed during the polishing process described herein. First peripheral region 60 therefore represents a portion of the first major surface 54 that was modified during such polishing processes and, in embodiments where a brush polishing process is employed, may include slurry flow lines or other markings of a polishing process. The first peripheral region 60 can have a maximum linear dimension 64 in the X-direction or the Y-direction (away from corners of the glass substrate 52). As described herein, particularly in embodiments where the glass substrate 52 is strengthened, it has been found that limiting the maximum linear dimension 64 to less than or equal to 200 μm , or less than or equal to 175 μm , or less than or equal to 150 μm , or less than or equal to 140 μm , or less than or equal to 130 μm , or less than or equal to 120 μm , or less than or equal to 110 μm , or less than or equal to 100 μm , or less than or equal to 90 μm , or even less than or equal to 80 μm can aid in preventing the beneficial effects of the glass substrate 52 being strengthened from being removed. As described herein, limiting the maximum linear dimension 64 can prevent layers of compressive stress in the glass substrate 52 from being polished off during any of the polishing processes described herein, thereby providing improved edge strength over articles fabricated using certain existing polishing processes.

[0079] As shown in FIG. 1B, the second major surface 56 includes a second peripheral region 70 extending outward from a boundary 72 to the polished edges 58. The second peripheral region 70 represents a portion of the second major surface 56 where material of the blank was removed during the polishing process. The second peripheral region 70 represents a portion of the second major surface 56 that was modified during the polishing process and may include slurry flow lines or other markings of a polishing process. It is beneficial to limit a maximum linear dimension 74 of the second peripheral region 70 in a similar manner as the maximum linear dimension 64 of the first peripheral region 60 to provide improved edge strength. In embodiments, material removal via the polishing process described herein is symmetrical so that the first and second peripheral regions 60 and 70 have substantially similar

shape. In embodiments, material removal is asymmetric so that one of the first and second major surfaces 54 and 56 has material removed over a larger area than the other. In such embodiments, the maximum linear dimensions 64 and 74 can differ from one another and the precise surface shapes of the first and second peripheral regions 60 and 70 can vary.

[0080] Various structural and compositional details of the glass substrate 52 will now be provided. In embodiments the glass substrate 52 has a thickness t that is substantially constant over the width and length of the glass substrate 52 (e.g., inward of the first and second peripheral regions 60 and 70). The thickness t is defined as a distance (in the Z-direction) between the first major surface 54 and the second major surface 56. In various embodiments, t may refer to an average thickness or a maximum thickness of the glass substrate 52 (inward of the boundaries 62 and 72). In addition, the glass substrate 52 includes a width W defined as a first maximum dimension of one of the first or second major surfaces 54, 56 orthogonal to the thickness t , and a length L defined as a second maximum dimension of one of the first or second major surfaces 54, 56 orthogonal to both the thickness and the width. In various embodiments, width W and the length L are a range from 5 cm to 250 cm

[0081] In various embodiments, thickness t is 2 mm or less. In particular, the thickness t is from 0.30 mm to 2.0 mm. For example, thickness t may be in a range from about 0.30 mm to about 2.0 mm, from about 0.40 mm to about 2.0 mm, from about 0.50 mm to about 2.0 mm, from about 0.60 mm to about 2.0 mm, from about 0.70 mm to about 2.0 mm, from about 0.30 mm to about 1.9 mm, from about 0.30 mm to about 1.8 mm, from about 0.30 mm to about 1.7 mm, from about 0.30 mm to about 1.6 mm, from about 0.30 mm to about 1.5 mm, from about 0.30 mm to about 1.4 mm, from about 0.30 mm to about 1.4 mm, from about 0.30 mm to about 1.703 mm, from about 0.30 mm to about 1.2 mm, from about 0.30 mm to about 1.1 mm, from about 0.30 mm to about 1.0 mm, from about 0.30 mm to about 0.90 mm, from about 0.30 mm to about 0.80 mm, from about 0.30 mm to about 0.70 mm, from about 0.30 mm to about 0.60 mm, or from about 0.30 mm to about 0.40 mm. In other embodiments, the t falls within any one of the exact numerical ranges set forth in this paragraph.

[0082] The composition of the glass substrate 52 is not particularly limited. In embodiments, the glass substrate 52, may be formed from any suitable glass composition comprising soda lime glass, aluminosilicate glass, borosilicate glass, boroaluminosilicate glass, alkali-containing aluminosilicate glass, alkali-containing borosilicate glass, and alkali-containing boroaluminosilicate glass.

[0083] In embodiments, the glass substrate 52 may be strengthened to comprise compressive stress that extends from a surface to a depth of compression (DOC). The

compressive stress regions are balanced by a central portion exhibiting a tensile stress. At the DOC, the stress crosses from a positive (compressive) stress to a negative (tensile) stress. As shown in FIG. 1B, in the depicted embodiment, the glass substrate 52 comprises a first layer of compressive stress 76 extending from the first major surface 54 to a first depth of compression (DOC₁) in the Z-direction and a second layer of compressive stress 78 extending from the second major surface 56 to a second depth of compression (DOC₂). A layer of tensile stress 80 extends between the first and second layers of compressive stress 76 and 78. The first and second layers of compressive stress 76 and 78 can be formed using a variety of techniques. For example, in embodiments, the glass substrate 52 can be strengthened mechanically by utilizing a mismatch of the coefficient of thermal expansion between portions of the glass to create a compressive stress region and a central region exhibiting a tensile stress. Alternatively, the glass substrate 52 may be strengthened thermally by heating the glass to a temperature above the glass transition point and then rapidly quenching.

[0084] In embodiments, the glass substrate 52 can be chemically strengthened by ion exchange. In the ion exchange process, ions at or near an outer surface 81 of the glass substrate 52 are replaced by – or exchanged with – larger ions having the same valence or oxidation state. The outer surface 81 represents a combination of the first major surface 54, the second major surface 56, and the plurality of polished edges 58. In embodiments in which the glass substrate 52 comprises an alkali aluminosilicate glass, ions in the surface layer of the article and the larger ions are monovalent alkali metal cations, such as Li⁺, Na⁺, K⁺, Rb⁺, and Cs⁺. Alternatively, monovalent cations in the surface layer may be replaced with monovalent cations other than alkali metal cations, such as Ag⁺ or the like. In such embodiments, the monovalent ions (or cations) exchanged into the glass article generate a stress.

[0085] Ion exchange processes are typically carried out by immersing a glass article in a molten salt bath (or two or more molten salt baths) containing the larger ions to be exchanged with the smaller ions in the glass article. It should be noted that aqueous salt baths may also be utilized. In addition, the composition of the bath(s) may comprise more than one type of larger ion (e.g., Na⁺ and K⁺) or a single larger ion. It will be appreciated by those skilled in the art that parameters for the ion exchange process, comprising, but not limited to, bath composition and temperature, immersion time, the number of immersions of the glass article in a salt bath (or baths), use of multiple salt baths, additional steps such as annealing, washing, and the like, are generally determined by the composition of the glass layer(s) of a decorated glass structure (comprising the structure of the article and any crystalline phases present) and the desired DOC and CS of the glass layer(s) of a decorated glass structure that results from

strengthening. Exemplary molten bath composition may comprise nitrates, sulfates, and chlorides of the larger alkali metal ion. Typical nitrates comprise KNO_3 , NaNO_3 , LiNO_3 , NaSO_4 and combinations thereof. The temperature of the molten salt bath typically is in a range from about 380°C up to about 450°C , while immersion times range from about 15 minutes up to about 100 hours depending on the glass thickness, bath temperature and glass (or monovalent ion) diffusivity. However, temperatures and immersion times different from those described above may also be used.

[0086] In embodiments, the glass substrate 52 may be immersed in a molten salt bath of 100% NaNO_3 , 100% KNO_3 , or a combination of NaNO_3 and KNO_3 having a temperature from about 370°C to about 480°C . In some embodiments, the glass substrate 52 may be immersed in a molten mixed salt bath comprising from about 5% to about 90% KNO_3 and from about 10% to about 95% NaNO_3 . In one or more embodiments, the glass article may be immersed in a second bath, after immersion in a first bath. The first and second baths may have different compositions and/or temperatures from one another. The immersion times in the first and second baths may vary. For example, immersion in the first bath may be longer than the immersion in the second bath. In embodiments, the glass substrate 52 may be immersed in a molten, mixed salt bath comprising NaNO_3 and KNO_3 (e.g., 49%/51%, 50%/50%, 51%/49%) having a temperature less than about 420°C (e.g., about 400°C or about 380°C). for less than about 5 hours, or even about 4 hours or less.

[0087] Compressive stress (CS) is measured using those means known in the art, such as by surface stress meter (FSM) using commercially available instruments such as the FSM-6000, manufactured by Orihara Industrial Co., Ltd. (Japan). Surface stress measurements rely upon the accurate measurement of the stress optical coefficient (SOC), which is related to the birefringence of the glass. SOC in turn is measured by those methods that are known in the art, such as fiber and four point bend methods, both of which are described in ASTM standard C770-98 (2013), entitled “Standard Test Method for Measurement of Glass Stress-Optical Coefficient,” the contents of which are incorporated herein by reference in their entirety, and a bulk cylinder method. As used herein CS may be the “maximum compressive stress” which is the highest compressive stress value measured within the compressive stress layer. In some embodiments, the maximum compressive stress is located at the surface of the glass article. In other embodiments, the maximum compressive stress may occur at a depth below the surface, giving the compressive profile the appearance of a “buried peak.”

[0088] DOC (e.g., DOC_1 and DOC_2) may be measured by FSM or by a scattered light polariscope (SCALP) (such as the SCALP-04 scattered light polariscope available from

GlasStress Ltd., located in Tallinn Estonia), depending on the strengthening method and conditions. When the glass article is chemically strengthened by an ion exchange treatment, FSM or SCALP may be used depending on which ion is exchanged into the glass article. Where the stress in the glass article is generated by exchanging potassium ions into the glass article, FSM is used to measure DOC. Where the stress is generated by exchanging sodium ions into the glass article, SCALP is used to measure DOC. Where the stress in the glass article is generated by exchanging both potassium and sodium ions into the glass, the DOC is measured by SCALP, since it is believed the exchange depth of sodium indicates the DOC and the exchange depth of potassium ions indicates a change in the magnitude of the compressive stress (but not the change in stress from compressive to tensile); the exchange depth of potassium ions in such glass articles is measured by FSM. Central tension or CT is the maximum tensile stress and is measured by SCALP.

[0089] With reference to FIG. 1B, in embodiments, DOC_1 and DOC_2 may be equal to or greater than about 0.05t, equal to or greater than about 0.1t, equal to or greater than about 0.11t, equal to or greater than about 0.12t, equal to or greater than about 0.13t, equal to or greater than about 0.14t, equal to or greater than about 0.15t, equal to or greater than about 0.16t, equal to or greater than about 0.17t, equal to or greater than about 0.18t, equal to or greater than about 0.19t, equal to or greater than about 0.2t, equal to or greater than about 0.21t. In some embodiments, DOC_1 and DOC_2 may be in a range from about 0.08t to about 0.25t, from about 0.09t to about 0.25t, from about 0.18t to about 0.25t, from about 0.11t to about 0.25t, from about 0.12t to about 0.25t, from about 0.13t to about 0.25t, from about 0.14t to about 0.25t, from about 0.15t to about 0.25t, from about 0.08t to about 0.24t, from about 0.08t to about 0.23t, from about 0.08t to about 0.22t, from about 0.08t to about 0.21t, from about 0.08t to about 0.2t, from about 0.08t to about 0.19t, from about 0.08t to about 0.18t, from about 0.08t to about 0.17t, from about 0.08t to about 0.16t, or from about 0.08t to about 0.15t. In some instances, DOC_1 and DOC_2 may be about 20 μm or less. In one or more embodiments, the DOC may be about 40 μm or greater (e.g., from about 40 μm to about 300 μm , from about 50 μm to about 300 μm , from about 60 μm to about 300 μm , from about 70 μm to about 300 μm , from about 80 μm to about 300 μm , from about 90 μm to about 300 μm , from about 100 μm to about 300 μm , from about 110 μm to about 300 μm , from about 120 μm to about 300 μm , from about 140 μm to about 300 μm , from about 150 μm to about 300 μm , from about 40 μm to about 290 μm , from about 40 μm to about 280 μm , from about 40 μm to about 260 μm , from about 40 μm to about 250 μm , from about 40 μm to about 240 μm , from about 40 μm to about 230 μm , from about 40 μm to about 220 μm , from about 40 μm to about 210 μm , from

about 40 μm to about 200 μm , from about 40 μm to about 180 μm , from about 40 μm to about 160 μm , from about 40 μm to about 150 μm , from about 40 μm to about 140 μm , from about 40 μm to about 130 μm , from about 40 μm to about 120 μm , from about 40 μm to about 110 μm , or from about 40 μm to about 100 μm .

[0090] In embodiments, the first and second layers of compressive stress 76 and 78 may have a CS (which may be found at the surface or a depth within the glass article) of about 200 MPa or greater, 300 MPa or greater, 400 MPa or greater, about 500 MPa or greater, about 600 MPa or greater, about 700 MPa or greater, about 800 MPa or greater, about 900 MPa or greater, about 930 MPa or greater, about 1000 MPa or greater, or about 1050 MPa or greater. In embodiments, the layer of tensile stress 80 exhibits a maximum tensile stress or central tension (CT) of about 20 MPa or greater, about 30 MPa or greater, about 40 MPa or greater, about 45 MPa or greater, about 50 MPa or greater, about 60 MPa or greater, about 70 MPa or greater, about 75 MPa or greater, about 80 MPa or greater, or about 85 MPa or greater. In some embodiments, the maximum tensile stress or central tension (CT) may be in a range from about 40 MPa to about 100 MPa.

[0091] With reference to FIGS. 1B and 1C, the shape of the outer surface 81 of the glass substrate 52 is particularly designed based on the strengthening of the glass substrate 52 (e.g., through one of chemical strengthening, thermal strengthening, or mechanical strengthening) so that the glass substrate 52 substantially retains a mechanical strength despite being cut from the blank via any of the near-net shaping processes described herein. In this regard, as described in greater detail herein, the polished edges 58 are formed by removing material from the edge of the workpiece via concentrated contact between brush filaments and the workpiece edge. That is, concentrated contact between the brush filaments and the first and second major surfaces 54 and 56 is avoided to limit the size of the first and second peripheral regions 60 and 70 such that the first and second layers of compressive stress 76 and 78 extend outward and are present on the polished edges 58. Portions of the polished edges 58 are therefore under compressive stress. As a result, entireties of the first and second major surfaces 54 and 56 are under compressive stress. Put differently no points on the first and second major surfaces 54 and 56 are under tensile stress. Particular design of the polishing process and edge profile described herein prevent any portion of the first and second layers of compressive stress 76 and 78 from being completely removed from the workpiece, thereby maximizing the edge strength of the glass substrate 52, as described herein.

[0092] With particular reference to FIG. 1C, the design of the edge profile will be described with greater particularity. As shown, the first peripheral region 60 of the first major surface 54

comprises a first region 82 (extending immediately outward from the boundary 62), a curved region 84, and an outer edge 86. The first region 82 represents a portion of the first major surface 54 that was modified during the polishing (via the polishing slurry flow described herein) but still has a substantially planar shape, deviating minimally from the X-Y plane in any perceptible pattern. Material removal via polishing slurry flow is slighter in the first region 82 than in the curved region 84, and so the overall shape of the first major surface 54 is minimally changed in the first region 82. In the curved region 84, the cross-sectional shape of the first major surface 54 deviates from the X-Y plane along a curve approximated by a relaxed spline. Such a shape is a result of controlled polishing slurry flow in interstitial regions between substrates in the polishing process described herein. Concentrated slurry flow results in removal of workpiece material in a relaxed spline shape, such that, within the curved region 84, a distance in the Z-direction between the first major surface 54 and the X-Y plane increases with increasing lateral distance (in the Y-direction) from the boundary 62 (see FIGS. 1A-1B). Material removal via the polishing slurry flow is gradual such that, even if a relatively large numbers of polishing cycles are conducted to form the polished edge 58 (e.g. 4 cycles, 5 cycles, 6 cycles, 7 cycles, 8 cycles, 9 cycles, 10 cycles), the lateral extent of the curved region 84 is limited to avoid removal of the first layer of compressive stress 76. In embodiments, the curved region 84 comprises a depth 88, represented by a maximum distance in the Z-direction between the curved region 84 and the X-Y plane, that is less than DOC_1 (preferably less than $0.75*DOC_1$, or even more preferably less than or equal to $0.5*DOC_1$) to facilitate a portion of the polished edge 58 being under compressive stress. For example, the depth 88 can be less than or equal to 200 μm , less than or equal to 100 μm , or preferably less than or equal to 90 μm , or even more preferably less than or equal to 80 μm . Material removal via the polishing process described herein will result in the depth 88 being at least 1 μm .

[0093] In embodiments, the curved region 84 comprises a width 90, represented by a maximum lateral distance in the Y-direction between the outer edge 86 and an inner boundary of the curved region 84, that is less than $2*DOC_1$ (preferably less than $1.75*DOC_1$ and even more preferably less than $1.5*DOC_2$). In embodiments, the width 90 is less than or equal to 200 μm , or even more preferably less than or equal to 150 μm , or even more preferably less than or equal to 125 μm , or even more preferably less than or equal to 100 μm . The width 90 is generally greater than the depth 88. As described herein, the depth 88 and width 90 can be controlled by controlling parameters (e.g., a particle size distribution associated with the polishing slurry) of the polishing process used to remove material from the workpiece. Control

of the polishing process to achieve the above dimensions of the first peripheral region 60 (and second peripheral region 70) facilitates achieving the advantaged edge profile described herein. Referring still to FIG. 1C, the outer edge 86 represents a boundary between the polished edge 58 and the first major surface 54. The outer edge 86 represents a line of separation between a region where material of the workpiece is aggressively removed during the polishing process (e.g., via engagement with a plurality of brush filaments) to form the polished edge 58 and the first peripheral region 60, where material removal is less aggressive. It has been found that avoiding sharp boundaries on the outer surface 81 (see FIGS. 1A-1B) aids in reducing stress concentrations in the glass substrate 52 during impact events and thereby provides improved edge strength. Accordingly, at the outer edge 86, the outer surface 81 may exhibit a minimum radius of curvature that is greater than or equal to $2 * t$ (preferably greater than or equal to $3 * t$, or even more preferably greater than or equal to $4 * t$). In embodiments, the minimum radius of curvature at the outer edge 86 is greater than or equal to 1 mm, greater than or equal to 1.5 mm, greater than or equal to 2.0 mm, or even greater than or equal to 2.5 mm. The minimum radius of curvature described herein can be measured using a commercially available optical CMM to inspect a cross-section of the part taken perpendicular to the measured edge.

[0094] The polished edges 58 are achieved via the polishing processes described herein. The polished edges 58 can exhibit any desired shape. In embodiments, the polished edges 58 can exhibit a substantially planar shape, with similar flatness attributes as the central portions of the first and second major surfaces 54 and 56. In embodiments, one or more of the polished edges 58 can exhibit a curvature (with a minimum radius of curvature that is greater than or equal to 1 mm and less than or equal to 5000 mm).

[0095] In embodiments, the polished edges 58 exhibit a relatively low surface roughness. For example in embodiments, the polished edges 58 exhibit an R_a value that is greater than or equal to 1 nm and less than or equal to 20 nm. As used herein, the term “ R_a value” refers to a surface roughness measure of the arithmetic average value of a filtered roughness profile determined from deviations from a centerline of the filtered roughness. For example, a R_a value may be determined based on the relation:

$$Ra = \frac{1}{n} \sum_{i=1}^n |H_i - H_{CL}| \quad (1)$$

where H_i is a surface height measurement of the surface and H_{CL} corresponds to a centerline (e.g., the center between maximum and minimum surface height values) surface height measurement among the data points of the filtered profile. Filter values (e.g., cutoff wavelengths) for determining the R_a values described herein may be found in ISO 25178.

Surface height may be measured with a variety of tools, such as an optical interferometer, stylus-based profilometer, or laser confocal microscope. Unless otherwise specified herein, Ra, rms, and PV values were measured via an optical interferometer. Alternatively or additionally, the polished edges 58 can exhibit a rms roughness (calculated from the same measurements used to determine the Ra value) that is greater than or equal to 1 nm and less than or equal to 30 nm. Alternatively or additionally, the polished edges can exhibit a PV surface roughness that is greater than or equal to 10 nm and less than or equal to 50 nm. As such, the polished edges 58 described herein can exhibit at least one of: (a) an Ra surface roughness that is greater than or equal to 1 nm and less than or equal to 20 nm; (b) a root mean squared surface roughness that is greater than or equal to 1 nm and less than or equal to 30 nm and (c) a peak to valley surface roughness that is greater than or equal to 10 nm and less than or equal to 50 nm. The polished edges 58 preferably exhibit each of (a), (b), and (c). The first and second peripheral regions 60 and 70 (see FIGS. 1A and 1B) may exhibit at least one of (or any of) (a), (b), and (c), while the portions of the first and second major surfaces 54 and 56 disposed inward of the boundaries 62 and 72 (unmodified in polishing) may exhibit each of (a), (b) and (c).

[0096] With reference to FIGS. 1B, another benefit associated with the polishing processes described herein is that they can be used on decorated parts with minimal damage to decorations applied to the parts. As shown, there is a decoration layer 92 disposed on the second major surface 56. The decoration layer 92 may be any suitable decoration for providing the glass substrate 52 a desired appearance. For example, in embodiments, the decoration layer 92 is a suitable black matrix ink applied by existing processes (e.g., inkjet printing, screen printing). In embodiments, the decoration layer 92 is a black ink comprising a thickness of less than 100 μm and exhibiting an optical density of at least 3.0 in the visible spectrum from 400 to 700 nm). The particular pattern formed on the second major surface 56 by the decoration layer 92 is not particularly limiting. For example, the decoration layer 92 may include a central opening (not depicted) having a peripheral shape corresponding to the peripheral shape of the glass substrate 52, such that the decoration layer 92 is a frame covering a periphery of the second major surface 56.

[0097] The decoration layer 92 can include an outer boundary 94 disposed proximate to the polished edges 58. In embodiments, the outer boundary 94 is disposed inward of the second peripheral region 70. As such, the outer boundary 94 may be formed during the polishing processes described herein, such that portions of the decoration layer 92 that are damaged during near-net shaping are removed during polishing to form crisp, visually pleasing boundaries. In embodiments, the outer boundary 94 is disposed a maximum lateral distance

(in a direction parallel to the X-Y plane and perpendicular to the nearest polished edge 58) from the nearest polished edge that is less than or equal to 150 μm (e.g., less than or equal to 125 μm , less than or equal to 100 μm , less than or equal to 90 μm , less than or equal to 80 μm , less than or equal to 70 μm , less than or equal to 60 μm , or even less than or equal to 50 μm) from the nearest polished edge 58 (and/or the polished edge 58 that the outer boundary 94 being measured extends parallel to). In embodiments where brush polishing is employed to obtain the edge profile described herein, the decoration boundary 94 may exhibit slurry flow lines that are visible in 50 to 100 times magnification images. The slurry flow lines are generally on the scale of 0.5 μm to 3 μm (in width). The first and second major surfaces 54 and 56 may be free of brush marks from a polishing brush, which are larger than the slurry flow lines and may disrupt the crisp edges of the decoration.

[0098] Compatibility of the polishing processes described herein with the decoration layer 92 facilitates the glass substrate 52 being formed in a process in which the workpiece is cut in relatively close proximity to boundaries of the material of the decoration layer 92 when disposed on the blank. Cutting in close proximity to decorative boundaries beneficially maximizes utilization of the blank and avoids material waste. The polishing processes described herein therefore facilitate cutting manufacturing costs via improved material utilization over existing processes where any damage to decorative material is avoided during near-net shaping.

[0099] Turning now to FIG. 2, a manufacturing process 200 is shown for fabricating the glass substrate 52 described herein with respect to FIGS. 1A-1C. Reference will be made to various components depicted in FIGS. 1A-1C to aid in describing the process 200. At block 202, a strengthened glass blank is provided. For example, a glass sheet may be fabricated using any known process where batch materials are melted and mixed in a suitable process and subjected to a forming process, such as a float process or a down-draw process. The glass sheet may then be subjected to a suitable strengthening process to form the blank. In embodiments, for example, an aluminosilicate glass sheet is formed by a fusion down-draw process at any of the thicknesses described therein to provide the thickness t desired for the glass substrate 52. The glass sheet may then be subjected to a suitable ion exchange process, such as those described herein with respect to FIGS. 1A-1C, to form the blank. As a result, the first and second layers of compressive stress 76 and 78 are formed in the blank.

[0100] At block 204, a decoration layer is applied to a major surface of the blank. The composition or appearance of the decoration layer is not particularly limiting. The decoration layer may be formed in a pattern on the major surface using any suitable technique (e.g., screen

printing, inkjet printing). In embodiments the decoration layer is patterned into a plurality of discrete regions on the major surface, with each region corresponding to a separate part to be formed from the blank. Each pattern may be separate from one another and/or represent a pattern associated with an individual part.

[0101] At block 206, the blank is near-net shaped into a plurality of workpieces. The workpieces may be near-net shaped using any suitable method. In embodiments, the workpieces may be near-net shaped using a mechanical score and break process wherein a where the blank is scored with an outline of the component to be formed and finished, and the component is mechanically separated from the larger sheet along the score line. In other embodiments, near-net shaping may be performed by nano-perforation and thermal separation, using for example, using laser systems supplied by Corning Laser Technologies (CLT). In some embodiments, near-net shaping may include a first step of laser nano-perforation and a second step of thermal separation via a CO₂ laser or other suitable laser device. In other embodiments, near-net shaping may include nano-perforation and self-separation (e.g. no second step of thermal separation may be needed). Near-net shaping processes via laser are preferred in that they are able to produce relatively flat edges and controlled proximate to the boundary of the decoration layer associated with a particular part so as to increase material utilization.

[0102] At block 208, edges of a workpiece are polished to remove material therefrom and form the glass substrate 52. In embodiments, the polishing may be performed via the batch brush polishing process described herein with respect to FIG. 3. In embodiments, the polishing may be performed using another suitable polishing process capable of performing more aggressive material removal (e.g., in terms of unit thickness per time) on the workpiece edge than the major surfaces to limit material removal from the major surfaces and to form the edge profile described herein with respect to FIGS. 1A-1C. For example, it has been determined that a fixed abrasive polishing wheel, such as those described in U.S. Patent No. 10,173,916 B2, hereby incorporated by reference in its entirety, can be used to fabricate glass substrates having the edge profile described herein. An example of such a process will be described herein in the Examples. However, it has been determined that the brush polishing method described herein with respect to FIG. 3 is preferred because the brush polishing method is more consistent and controllable. Additionally, abrasive polishing wheels include abrasive particles exceeding 10 μm in size, leading to flaws of comparable size on the polished edges 58. Such flaws can degrade edge strength. The brush polishing process described herein with respect to FIG. 3 is preferred because of material removal through the combination of brush contact and slurry

flow. The combination of relatively soft brush filaments and fine slurry adding chemical action to edge finishing via brush polishing produces much smaller flaws ($\leq 2\mu\text{m}$) in the final product thereby producing advantaged mechanical edge strength.

[0103] At block 210, after the brush polishing, coatings and/or surface treatments are applied to the surface of the glass substrate 52 that is not occupied by the decoration layer 92. Such coatings and/or surface treatments can include any suitable combinations of known additions to provide any desired functionality (e.g., optical performance) to the glass substrate 52. For example, in embodiments, at block 210, an anti-glare surface treatment is applied to the first major surface 54 (e.g. via a suitable etching or sandblasting technique). In embodiments, at block 210, an anti-reflective coating is applied to an entirety of the first major surface 54 (including the first peripheral region 60). The anti-reflective coating may include alternating layers of relatively high and low refractive index materials configured to provide the glass substrate 52 with a suitable optical performance. Alternatively or additionally, the surface treatments may include application of an easy-to-clean coating. Such coatings may be applied at elevated temperatures using a suitable physical or chemical deposition process (e.g., physical vapor deposition, chemical vapor deposition, sputtering), where the glass substrate is heated to an elevated temperature (in excess of 150°C). It has been found that certain existing brush polishing processes lead to chipping at the edges of the parts and that decoration of these chips by such coatings increases the visibility of these defects. The polishing processes described herein (particularly, the brush polishing processes), however, do not suffer from such defects as no such chipping is observed post decoration. Examples of coatings and surface treatments that may be applied to the glass substrate 52 are described in U.S. Patent Application No. 16/977,332, entitled “Anti-Reflective Coatings and Articles and Methods of Forming the Same,” hereby incorporated by reference in its entirety.

[0104] A particular optical phenomena is observed when an anti-reflective coating is deposited on the first major surface 54 using a physical vapor deposition process. Particularly, the anti-reflective coating is deposited over the entire first major surface 54 (including the first peripheral region 60) using a coating that is configured to provide a certain optical performance on the central (unmodified) portion of the first major surface 54. The coating is configured to exhibit transparency in the visible spectrum when the glass substrate 52 is viewed normally from the first major surface 54. However, when the first peripheral region 60 (particularly the curved region 84) is viewed at a local surface normal thereof, the curved shape of the first major surface 54 causes the glass substrate 52 to exhibit a golden hue. When illuminated with a diffuse D65 illuminant and viewed in a direction normal to the first major surface 54 at the

first peripheral region 60, the glass substrate 54 exhibits a color with an a^* value (according to the CIELAB color space) that is greater than 0. This color is different from that exhibited by when the glass substrate 54 is viewed in a direction normal to the central portion of the first major surface 54.

[0105] Referring now to FIG. 3, a process 300 of polishing a workpiece near-net shaped from a glass sheet blank is shown, according to an example embodiment. The process 300 may be used to remove material from an edge and surfaces of a workpiece and form the glass substrate 52 described herein with respect to FIGS. 1A-1C. For example, the process 300 may be used as a component of the process 200 described herein with respect to FIG. 2. The process 300 is a brush polishing process wherein contact between brush filaments associated with a polishing brush is used to remove material more aggressively (in terms of material volume per unit time) on the edge of the workpiece than on the major surfaces of the workpiece. A relatively high flow of a polishing slurry is used to remove material less aggressively at peripheral regions of the major surfaces of the workpiece so as to form the polished edges 58 and first and second peripheral regions 60 and 70 described herein.

[0106] In embodiments, the process 300 is a component of a batch manufacturing process where a plurality of the glass substrates described herein are formed from conjunction with one another. For example, as described herein, a plurality of workpieces may be cut from a glass sheet blank and edge polished simultaneously using the process 300. Accordingly, at block 302, after near-net shaping (e.g., after block 206 of the process 200 described herein with respect to FIG. 2), a workpiece is arranged in a stack between first and second interposers. FIGS. 4A and 4B depict an example stack 400 comprising a plurality of workpieces 402 and a plurality of interposers 404 interleaved between the plurality of workpieces, according to an example embodiment. The plurality of workpieces 402 may have been cut from a sheet of glass (e.g., after strengthening and decoration, as described herein with respect to the process 200). For example, each of the plurality of workpieces 402 may have a structure similar to that of the glass substrate 52 described herein with respect to FIGS. 1A-1C, but prior to polishing. As shown, the substrates include as-cut edges 405, being in a condition that varies depending on the manner with which near-net shaping is conducted. The as-cut edges 405 may have a reduced edge strength as compared to the strengthened substrate from which they are formed due to relatively large flaws contained therein (e.g., induced from the cutting process). While in FIGS. 4A and 4B, the plurality of workpiece 402 are depicted to be identical in structure, it should be understood that embodiments are also contemplated where the plurality of workpieces 402 differ from one another in at least one respect (e.g., in terms of workpiece

thickness or glass composition) are also contemplated and within the scope of the present disclosure.

[0107] The plurality of interposers 404 serve to separate the plurality of workpieces 402 in order to facilitate formation of the desired edge profile, as described herein. The plurality of interposers 404 may be formed using a variety of different techniques in accordance with the present disclosure. For example, in embodiments, the plurality of interposers 404 are pre-formed articles of a suitable material and arranged between the plurality of workpieces 402. In such embodiments, the plurality of interposers 404 can be precision patterned to a precise shape based on the desired peripheral shape of the glass substrate 52. In such precision patterning, interposer precursor material is disposed on the one or more of the workpieces 402 in a desired pattern (e.g., cross-hatch, stripe, dot matrix). In such embodiments, the plurality of interposers 404 can be formed on the plurality of workpieces 402. For example, the plurality of interposers 404 can be formed by depositing a liquid precursor material onto a surface of at least one of the plurality of workpieces 402 (e.g., using screen printing, inkjet printing, or other suitable process), which can be subsequently solidified into the plurality of interposers. Such precision patterning is preferable because it avoids complexities associated with arranging preformed interposers, while also enabling efficient switch of interposer patterns for discrete parts. Inkjet printed interposers are preferred to the precision, speed, efficiency, and minimal material waste.

[0108] In embodiments, each of the plurality of interposers 404 may have a planar shape with first and second side surfaces 407. In embodiments, each of the plurality of interposers 404 can be sized and shaped to correspond with a particular workpiece or a desired end shape associated with the glass substrate 42. For example, where the glass substrate 52 has a circular perimeter shape, the corresponding interposer may also have a circular perimeter shape. In embodiments, the plurality of interposers 404 are sized based on a desired size of the glass substrate 52 after polishing. For example, in embodiments, each of the plurality of interposers 404 is parallelepiped-shaped like the glass substrate 52 described herein with respect to FIGS. 1A-1C and comprises a length L and a length W corresponding to those of the glass substrate 52. In embodiments, the plurality of interposers 404 can be sized to be slightly smaller than the finished glass substrate 52 after polishing. For example, where the substrate is configured to have a final length of 100mm, the corresponding interposer may have a length L of 99mm, 98mm, 97mm, 96mm, 95mm, or a different length. Such a structure may facilitate access to the surfaces of the workpieces 402. The plurality of interposers 404 may have smaller or larger dimensions sized to correspond with the particular substrate(s) to be processed.

[0109] The plurality of interposers 404 are disposed such that each of the plurality of interposers 404 comprises an ingress 406 from an as-cut edge 405 of a nearest one of the plurality of workpieces 402. Ingress 406 represents a maximum lateral distance (measured in a direction parallel to the major surfaces of the nearest one of the plurality of workpieces 402) that an interposer edge is separated from the as-cut edges 405 of the nearest workpiece. The extent of the ingress 406 is determined by a size difference between the plurality of workpieces 402 and the plurality of interposers 404. In embodiments, the plurality of interposers 404 are sized such that the ingress 406 is 0.0 mm (e.g., the interposers may have the same size as the workpieces and have aligned peripheral edges). In embodiments, the interposers and workpieces are sized and positioned (e.g., with the plurality of interposers 404 sized smaller than the plurality of workpieces 402 and co-centered) such that the ingress 406 is less than or equal to 10.0 mm (e.g., less than or equal to 5.0 mm, less than or equal to 2.0 mm, less than or equal to 1.0 mm).

[0110] Each of the plurality of interposers 404 can have a thickness 408 that determines the spacing between adjacent ones of the plurality of workpieces 402. In some embodiments, the thickness 408 may be between approximately 0.01 and approximately 10 times a thickness of a corresponding substrate to be formed and finished. For example, where glass substrate 52 has a thickness of 1 mm, the plurality of interposers may have a thickness 408 of between approximately 0.01 mm and approximately 10 mm. The thickness 408 of the plurality of interposers 404 may be sized to control exposure of substrate material to brush filaments, as described below.

[0111] In some embodiments, the plurality of interposers 404 may have one or more through holes (not depicted) extending between the two side surfaces 407. Each interposer may have between 1 and 10, or more, through holes symmetrically or otherwise strategically spaced across the interposer. In some embodiments, the through holes may each be configured to receive a stabilizer or stabilizing material. Stabilizers or stabilizing material may include one or more rubbers or other moldable materials configured to have a higher coefficient of friction against the workpiece material, as compared with the surrounding interposer material. In some embodiments, the stabilizers may be readily removable from the through holes. In some embodiments, arranging the substrate between a first and second interposer may include placing a stabilizer or stabilizing material into each through hole before, during, or after each interposer is arranged in the stack 400.

[0112] In embodiments, up to 5, up to 10, up to 20, up to 50, up to 100, up to 200, up to 300, up to 400, or up to 500 substrates may be arranged together in the stack 400. Endcaps

or chucks may be arranged at each end (e.g., top and bottom) of the part stack in some embodiments. Endcaps or chucks may be constructed of one or more metals or other suitable materials. In some embodiments, interposers may be screen printed directly onto substrates. For example, a first substrate may be positioned in a stack, an interposer having desired shape and dimensions may be screen printed directly onto a side surface of the substrate, and a second substrate may be arranged in the stack over the printed interposer. In such embodiments, the interposers may be mechanically and/or chemically removed after brushing operations.

[0113] Referring again to FIG. 3, after the workpiece is arranged in the stack, at block 304, a compressive force is applied to the stack 400. The compressive force is represented by the arrows 410 in FIGS. 4A and 4B. For example, where the workpiece is arranged between first and second interposers, a compressive force may be applied to the first interposer, so as to compress the substrate and interposers from a first side, to the second interposer, so as to compress the substrate and interposers from a second side, or to both the first and second interposers. The compressive force may be applied using any suitable means and may range between approximately 1 psi and approximately 1000 psi. In some embodiments, the magnitude of pressure or force applied to the stack 400 may depend on the dimensions and/or number of workpieces. For example, where one or more workpieces in the stack have a length and width of 100 mm, a compressive force of between approximately 650-700 psi may be applied to the stack 400. As another example, where one or more workpieces in a stack are square shaped with a diagonal length of 635 mm, a compressive force of between approximately 30-40 psi may be applied to the stack 400. It is to be appreciated that the compressive force may be applied with a surface area large enough to distribute the compressive force and not cause cracking or breakage of the 400. The compressive force may be configured to hold the workpieces and interposers together in the stack 400 and generally prevent slippage or twisting of the components with respect to one another. The compressive force may be applied using any suitable means. In some embodiments, for example, a clamp may be arranged on the stack and a nut or bolt may be tightened to apply the desired force.

[0114] At block 306, the workpiece edges are brushed to form the glass substrate 52. The brushing may include contacting the as-cut edges 405 (see FIGS. 4A-4B) with a brush and a polishing material or slurry. The brush and slurry may be configured to remove material from the as-cut edges 405 in order to remove chips, cuts, or other flaws therefrom. Additionally, in some embodiments, the brush and slurry may be configured to simultaneously shape the edge surface of the substrate by mechanically and/or chemically removing substrate material to achieve a desired shape.

[0115] It has been found that the beneficial edge profile described herein with respect to FIGS. 1A-1C can be formed by concentrating contact between filaments of the brush and the workpieces at the as-cut edges 405. This can be achieved by configuring the brush and polishing slurry flow as described herein. FIGS. 4A-4B depict a rotary brush 412 that may be used to brush polish the as-cut edges 405 to remove material from the plurality of workpieces 402 and form a plurality of the glass substrate 52 described herein with respect to FIGS. 1A-1C in a batch fabrication process. The rotary brush 412 generally includes a base portion 414 and a plurality of brush filaments 416 extending from the base portion 414. The base portion 414 may be rotatable about an axis of rotation 418 and the plurality of brush filaments 416 may extend radially outward from the base portion 414 so that the plurality of brush filaments 416 contact the as-cut edges 405 of the plurality of workpieces 402. FIG. 4A depicts the rotary brush 412 translated relative to the stack 400 (e.g., above the stack 400) to illustrate the lateral positioning that the rotary brush 412 may take relative to the stack 400 during brush polishing. As shown, the rotary brush 412 may be positioned relative to the stack 400 so that an engagement length 420 (also termed as “engagement” herein) of the plurality of brush filaments 416 contact the as-cut edges 405. The engagement length 420 may represent a maximum the extent that the brush filaments contact the plurality of workpieces 402. Material of the plurality of workpieces 402 can be removed more aggressively with a greater engagement length (holding other factors of the filaments, such as diameter, overall length, and material constant). As described herein, it may be preferable to provide an engagement length 420 that is at least one third of a minimum length of the plurality of brush filaments 416 to facilitate relatively aggressive material removal and relatively low amounts of polishing time.

[0116] In embodiments, the plurality of brush filaments 416 comprise tubular bodies with a length along a central axis thereof and a diameter measured in a direction perpendicular to the central axis. The plurality of brush filaments 416 may be constructed of one or more polymeric, resin materials, or carbon fiber materials in some embodiments. In other embodiments, other suitable filament materials may be used. In embodiments, the plurality of brush filaments 416 may each have a diameter of not more than 0.500 mm. It is preferable to avoid brush filament diameters greater than 0.300 mm to avoid noticeable brush marks on the polished edges in certain implementations. Accordingly, in some embodiments, the plurality of brush filaments 416 may have a diameter of between approximately 0.01 mm and approximately 0.300 mm. Filaments may have a circular or polygonal cross-sectional shape in some embodiments. In embodiments, the plurality of brush filaments may have a length of between approximately 1 mm and approximately 200 mm. In embodiments, portions of the

lengths of the plurality of brush filaments 416 are inserted into the base portion 414. Filaments of a brush may have varied lengths and/or varied diameters in some embodiments.

[0117] Moreover, brush filaments may be arranged in discrete tufts or bundles, each tuft or bundle having a diameter of between approximately 1.0 mm and approximately 10.0 mm. Individual filaments or tufts of filaments may be arranged in a particular pattern on the brush base. For example, bundles or tufts may be arranged in a straight, spiral, staggered, random or other pattern. Additionally, a brush may have a brush density (or filament density) of between approximately 10% and approximately 95%, or between approximately 30% and approximately 90%, or between approximately 50% and approximately 85%. In at least one embodiment, a brush of the present disclosure may have a brush density of approximately 68.5%. In other embodiments, filaments and tufts may have any other suitable sizing and configuration.

[0118] In embodiments, the rotary brush 412 is configured to rotate about the axis of rotation 418 while it is moved laterally along an edge of the stack 400, while the substrate and 414 is fixed. The lateral positioning of the rotary brush 412 during such movement may be set to achieve a desired engagement length 420 between the plurality of brush filaments 416 and the as-cut edges 405. In embodiments, the stack 400 may additionally or alternatively be configured to rotate about a central axis of the stack 400, which may be parallel to axis of rotation 418. In some embodiments, the brushing step may be performed by rotating the rotary brush 414 in a first direction and additionally rotating the stack 400 in an opposing second direction. This may be particularly useful where the workpieces have a round planar shape. It is to be appreciated that a brushing process of the present disclosure may operate to polish an entire perimeter edge of a substrate using a single pass polar motion, and without a need for corner dwelling or rounding motions.

[0119] The rotary brush 412 may be operated to apply a polishing material or slurry to the substrate. The polishing material or slurry may be configured to chemically and/or mechanically remove substrate material to simultaneously shape and/or polish the periphery of the plurality of workpieces 402. In some embodiments, the polishing material may be or include an abrasive slurry, such as a cerium oxide or diamond slurry. In some embodiments, the polishing material may include cerium oxide or another abrasive or chemical abrasive with a grain size of between approximately 0.01 micrometers and approximately 15.0 micrometers, or between 0.05 and 7.0 micrometers, between 0.1 and 1.0 micrometers, or between 0.1 and 0.5 micrometers. In at least one embodiment, the polishing material may have a cerium oxide or other abrasives or chemical abrasives having a grain size of between approximately 0.1 and

approximately 0.3 micrometers. In embodiments, the polishing material may have a d50 grain size that is greater than or equal to 0.5 μm (e.g., approximately 0.5 μm , 0.6 μm , 0.7 μm , 0.8 μm , 0.9 μm , 1.0 μm , 1.1 μm , 1.1 μm , 1.2 μm , 1.3 μm , 1.4 μm , 1.5 μm , 1.6 μm , 1.7 μm , 1.8 μm , 1.9 μm , 2.0 μm , 2.1 μm , 2.2 μm , 2.3 μm , 2.4 μm , 2.5 μm , 2.6 μm , 2.7 μm , 2.8 μm , 2.9 μm , 3.0 μm or any size between such values). In embodiments, the polishing material may have a d95 grain size that is greater than or equal to 2.0 μm (e.g., approximately 2.0 μm , 2.1 μm , 2.2 μm , 2.3 μm , 2.4 μm , 2.5 μm , 2.6 μm , 2.7 μm , 2.8 μm , 2.9 μm , 3.0 μm , 3.1 μm , 3.2 μm , 3.3 μm , 3.4 μm , 3.5 μm , 3.6 μm , 3.7 μm , 3.8 μm , 3.9 μm , 4.0 μm , 5.0 μm , 6.0 μm , 7.0 μm , 8.0 μm , 9.0 μm , 10.0 μm , 11.0 μm , 12.0 μm , 13.0 μm , 14.0 μm , 15.0 μm , or any grain size between such values). The cerium oxide slurry or other polishing material may have an alkalinity ranging from a pH of 6 to a pH of 11. In at least one embodiment, the polishing material may include a DND Dia-Sol Nanodiamond in 50 ct/liter with a diamond abrasive size ranging from approximately 30 nm to approximately 100 micrometers. Other polishing materials, including chemical and/or mechanical polishing materials may be used in other embodiments. In some embodiments, multiple polishing materials may be used consecutively or simultaneously.

[0120] Properties of the polishing material used during the polishing process can determine the shape of the particular edge profile achieved. It is believed that the d50 grain size of the polishing material establishes a lower bound for the depth 88 and width 90 of the curved region 84 described herein (see FIG. 1C). Generally, a larger d50 grain size will increase the size of the curved region 84 (e.g., in terms of both the depth 88 and width 90) because material removal on the major surfaces of the plurality of workpieces 402 generally occurs due to concentrated slurry flow. Limiting the d50 grain size to less than or equal to 3.0 μm has been found to effectively limit the size of the curved region 84 to preserve the first layer of compressive stress 76.

[0121] In some embodiments, the rotary brush 412 may be configured for receiving and distributing the polishing material. For example, the base portion 414 may have perforations or channels configured for ejecting polishing material from the brush base onto the filaments and substrate. Perforations may be distributed throughout the base portion 414. Polishing material may be expelled through the perforations via an extrusion system or via centripetal force of a rotating brush. Perforations may have a circular, polygonal, or any other suitable cross-sectional shape with any diameter suitable for achieving a desired flow rate of a polishing material having a defined viscosity. In some embodiments, the base portion 414 may

have a rotary union configured to enable continuous polishing material recharging from an external source as needed.

[0122] During the brushing operation, the rotary brush 412 may be driven at a rotational speed of between approximately 10 and approximately 1000 rpm. In embodiments, the rotary brush 414 is driven at a relatively high rotational speed (e.g., greater than or equal to 100 rpm, greater than or equal to 200 rpm, greater than or equal to 300 rpm, greater than or equal to 400 rpm, greater than or equal to 500 rpm, greater than or equal to 600 rpm, greater than or equal to 700 rpm, greater than or equal to 800 rpm) to facilitate generating a polishing slurry flow velocity that is sufficiently high to enter interstitial areas between the plurality of workpieces 402 and polish the major surfaces thereof. The rotary brush 412 may also be driven at a linear speed around the periphery of the stack 400 that is from 100 m/min to 1000 m/min). Such high polishing slurry flow velocity aids in creating the curved region 84 described herein with respect to FIGS. 1A-1C. In embodiments, a brush may be driven with a linear speed along an edge of the substrates of between approximately 1 and approximately 1000 m/min. Relatively low linear speeds (e.g., less than or equal to 100 mm/min, less than or equal to 75 mm/min, less than or equal to 50 mm/min, less than or equal to 40 mm/min, less than or equal to 30 mm/min) are preferred to facilitate removal of a relatively large amount of material from the as-cut edges 405 during each pass of the rotary brush 414. As used herein, the term “polishing pass” refers to movement of the rotary brush 414 around an entire periphery of the stack 400 via relative movement between the rotary brush 414 and the stack 400. It is desired to obtain the edge profile described herein with respect to FIGS. 1A-1C using a minimal number of brush cycles. Using relatively low brush translation speeds aids in achieving this goal. In aspects, the mechanical strength and edge profiles described herein can be achieved in less than or equal to 6 polishing passes, less than or equal to 5 polishing passes, less than or equal to 4 polishing passes, less than or equal to 3 polishing passes, less than or equal to 2 polishing passes, or even a single polishing pass. Lower numbers of passes are enabled through relatively high values for the engagement distance length (e.g., greater than or equal to a third of a maximum length of the plurality of brush filaments 416), especially when the filaments have diameters greater than 0.1 mm.

[0123] Brushing may be performed until a desired edge profile is achieved and until a maximum flaw size or average flaw size on the substrate edge is reduced to less than 3 micrometers, less than 2 micrometers, or less than 1 micrometer. The brushing step may operate to form a desired edge shape on the glass substrate 52, such as that described herein with respect to FIGS. 1A-1C. In embodiments, the brushing step may include a single stage

brushing step. That is, in some embodiments, a single brush may be used with a suitable number of passes over the edge surface to both shape and polish the edges. In other embodiments, brushing may be performed in multiple steps using, for example, more than one brush and/or more than one polishing material. For example, a first brushing step may be performed using a first brush and polishing material having a first grain size, and a second brushing step may be performed using the brush and a polishing material having a second, smaller grain size.

[0124] It has been found that the edge profile described herein with respect to FIGS. 1A-1C can be formed in a variety of different ways using the rotary brush 414. Generally, embodiments where the rotary brush 414 is constructed and operated to aggressively remove material from the as-cut edges 405 are preferred because they provide process efficiencies by reducing the amount of polishing passes needed and reduce processing times to provide finished substrates. Such aggressive material removal may be achieved by using brush filaments with diameters greater than 0.1 mm (e.g., approximately 0.2 mm). Moreover, in such aggressive material removal embodiments, the engagement length 420 in each polishing pass may be greater than or equal to 1/3 of a maximum length of the plurality of brush filaments 416. In embodiments, to facilitate aggressive material removal, the engagement length 420 may be greater than or equal to 6 mm (e.g., greater than or equal to 6 mm and less than or equal to 8 mm when the plurality of brush filaments 416 have lengths less than or equal to 20 mm, greater than or equal to 12 mm and less than or equal to 20 mm when the plurality of brush filaments have lengths that are greater than or equal 25 mm and less than or equal to 50 mm).

[0125] In embodiments with aggressive material removal via the rotary brush 414, contact between the plurality of brush filaments 416 and the plurality of workpieces 402 is concentrated on the as-cut edges 405 by limiting a minimum thickness 408 associated with the plurality of interposers 404 to being less than a maximum diameter of the plurality of brush filaments 416. For example, the minimum thickness 408 can be less than or equal to 0.75 times the maximum diameter of the plurality of brush filaments 416. When the plurality of brush filaments 416 have a diameter of 0.2 mm, for example, the minimum thickness 408 is less than 0.2 mm (e.g., less than or equal to 0.15 mm, less than or equal to 0.1 mm, less than or equal to 0.05 mm, greater than or equal to 0.01 mm and less than 0.15 mm). Such spacing beneficially prevents the ends of the plurality of brush filaments 416 from contacting the major surfaces of the plurality of workpieces 402, which prevents removal of excess material therefrom and prevents removing layers of compressive stress in the plurality of workpieces 402 present from strengthening thereof. As a result, the major surfaces of the plurality of workpieces 402

(corresponding to the first and second major surfaces 54 and 56 of the glass substrate 52) may be devoid of brush marks and only include slurry flow lines from the polishing slurry flow. Such slurry flow lines may generally have maximum widths that are less than or equal to a D95 grain size associated with the slurry (e.g., less than or equal to 15 μm , or even less than or equal to 3 μm in some embodiments). As a result of the lack of brush marks, the first and second peripheral regions 60 and 70 of the glass substrate 52 may exhibit a lower PV surface roughness value than the polished edges 58, which may include brush marks (e.g., having a maximum width greater than 5 μm or even greater than or equal to 10 μm).

[0126] The edge profile described herein with respect to FIGS. 1A-1C can also be achieved with more passive material removal via the rotary brush 412. In such passive embodiments, the thickness 408 of the plurality of interposers 404 is not particularly limited and may be greater than the diameters of the plurality of brush filaments 416. Such passive material removal can be achieved by limiting the brush filament diameter to less than or equal to 0.1 mm. In such embodiments, a wide variety of filament lengths (e.g., from 18 mm to 36 mm) and values for the engagement length 420 can be used (e.g., from 7 mm to 24 mm) given such low brush filament diameters. Alternatively or additionally, such passive material removal can also be achieved by limiting the engagement length 420 to less than one fifth of a maximum length of the plurality of brush filaments 416 when filaments having diameters greater than 0.1 mm are used. Such passive engagement generally prevents the rotary brush 412 from removing material on the major surfaces of the plurality of workpieces 402.

[0127] One advantage of the brush polishing process described herein is that the advantaged edge profile described herein can be achieved with relatively small amounts of material removal from the plurality of workpieces 402. In embodiments, material removal from the as-cut edges 405 via contact with the plurality of brush filaments 416 is limited to less than 50 μm , measured in a direction extending perpendicular to the as-cut edges 405. For example, in embodiments, the polished edges 58 are formed by removing from 10 μm to 50 μm of material from each of the as-cut edges 405 associated with one of the plurality of workpieces 402. In examples, two polishing passes have been found to remove from 20 μm to 30 μm of material from the as-cut edges 405 and result in the advantaged edge profile described herein. Such limited material removal improves material utilization in forming a plurality of glass substrates 52 from a single glass sheet blank.

[0128] Referring back to FIG. 3, after the brush polishing process is complete, at block 308, the process 300 may include cleaning and other downstream process steps. For example, after the brushing step is completed and the substrate edges are shaped and polished, the

substrate may be removed from the interposer stack, and the substrate may be cleaned by any suitable cleaning methods to remove polishing material, substrate dust, or other materials from the substrate surface. Cleaning may include rinsing or a water bath, for example. Additional downstream processes may include decoration such as printed inks, attachment of electronic components, additional strengthening such as IOX strengthening processes, and/or other downstream processes. In some embodiments, polished substrate edges may be further strengthened by an etching treatment.

[0129] It is to be appreciated that, in some embodiments, the process 300 described above may operate to simultaneously form and finish an edge surface of a substrate without mechanical grinding. That is, edge chamfering or other edge shaping may be provided by chemical and/or mechanical interaction between the polishing material and the substrate material as the polishing material is brushed over the edge surface. The process described above may operate to form and shape an edge surface without inflicting the damage that mechanical grinding, such as from grinding wheels, often produces. It is further to be appreciated that, without scratches, chips, and/or other flaws inflicted by mechanical grinding, a relatively high edge strength may be achieved using the process described above.

[0130] The process 300 described above may provide for a finished substrate with a relatively high edge strength. As used herein, the term “edge strength” refers to a B10 value associated with a Weibull distribution associated a plurality of the glass substrates 52 (e.g., obtained from a single batch formed from a stack) when each of the substrates is tested for mechanical edge strength using a four-point bend test in accordance with ASTM C158-02. Referring now to FIG. 5, an apparatus 150 used for determining the edge strength of substrates formed using the processes 200 and 300 described herein is shown. FIG. 5 depicts the glass substrate 52 undergoing an edge strength test using an apparatus 150 after polishing. As shown, the apparatus 150 comprises two first side load points 152 and two second side load points 154, which are bars that contact the glass surface in a line perpendicular to the edges intended for flexure. The two first side load points 152 and the two second side load points 154 have blunt, radiused ends such that they can generate stress in the glass substrate 52 without forming surface flaws in the location they contact. For example, the ends of the first side load points 152 and the two second side load points 154 may comprise a 5 mm radius. The first side load points 152 are shown in contact with the first major surface 54 and the second side load points 154 are shown in contact with the second major surface 56. The first side load points 152 are laterally spaced nearer to one another than the second side load points 154. In operation, the first side load points 152 translate in a first direction 153 to apply a force to the first major

surface 54, which causes the second side load points 154 (which do not translate) to also apply force in a second direction 155, opposite the first direction 153. For example, the first side load point 152 may translate in the first direction at a velocity of 5 mm/second to apply a force to the glass substrate 52.

[0131] While not intending to be limited by the theory, the apparatus 150 places a large region of the glass substrate 52 under approximately uniform stress. In operation, the applied force is increased and measured as a function of time until glass substrate 52 breaks along contour 170. The maximum applied force corresponds to the force that causes the glass substrate 52 to break at one of the polished edges 58. Using the dimensions of the glass substrate 52 and the maximum applied force, the stress at breakage can be calculated. The following formula may be used to calculate the stress at failure, in units of megaPascals (MPa):

$$Stress(MPa) = \frac{3 * L1 * F}{4 * t^2 * W} \quad (2)$$

[0132] Where L1 is the support span distance (mm), which is the distance between the two second side load points 154, F is the applied load (Newtons), W is the width of the transparent workpiece 160 (mm), and t is the thickness of the transparent workpiece 160 (mm). In measurements taken herein, W = 50 mm, L1 is 36 mm, and t = 1.3 mm. The above assumes the span under load, which is the distance between the two first side load points 152, is ½ the distance of the support span distance L1 holding the glass substrate 52. An individual glass substrate 52 may have a break resistance that is higher or lower, but on average such 4-point bend measurements characterize a distribution of parts. Such a distribution mean and its standard deviation can be reasonably characterized by breaking 5-10 glass substrates 52 fabricated in a batch, with more statistics being beneficial. In the case of edge strength, when the glass substrate 52 is subjected to a 4-point bend, it is generally the flaws along the polished edges 58 that are activated by the imparted stress, so the failure stress is measuring the “strength” of that outer edge.

[0133] In embodiments, the glass substrate 52 formed via the processes described herein may have a mechanical edge strength of least 300 MPa, at least 500 MPa, at least 700 MPa, at least 900 MPa, at least 1 GPa, at least 1.25 GPa, or more. Edge strength values may vary depending on the level of ion-exchange strengthening and thickness of the glass substrate 52. It should be noted that, unless otherwise noticed, mechanical edge strength values described herein are without post-polishing strengthening treatments (e.g., chemical strengthening, edge surface etching).

Examples

[0134] Embodiments of the present disclosure may be further understood in view of the following examples.

[0135] *Counter Examples*

[0136] In a first set of counterexamples, a quantity of 100.15mm x 100.15mm x 1.1mm workpieces produced by laser singulation of fully chemically strengthened Corning Gorilla™ Glass 3. The workpieces were formed in a stack for brush polishing, wherein individual thin glass parts were separated within this stack with PTFE interposers substantially smaller in dimension (96mm x 96mm x 1.1mm) than the corresponding thin glass substrates. Orange neoprene stabilizers were added to prevent parts from sliding apart in the stack. The stack was brush polished using a rotary brush with resin-filled filament brushes characterized by filament length of 18mm, filament diameter of 0.200mm, and standard (33 wind) brush density. Brush rotational speed was set to 800 rpm, feed rate was fixed at 27.5 mm/min, engagement length was set to 6 mm, and the polishing test was executed for 6 full brush polishing cycles.

[0137] The brush polishing process used to fabricate the first set of counterexamples does not follow the guidelines provided with respect to the process 300 described herein. The engagement length (6 mm) was relatively aggressive given the 0.2 mm filament diameter and 18 mm filament length, and the workpieces were separated by much more than the filament diameter. This brush polishing setup therefore fails to adequately concentrate contact between the brush filaments and the as-cut edges and have excess contact between the brush filaments and major surfaces. FIG. 6 is a microscope image of one of the counterexamples fabricated in this process. As shown, FSM measurements conducted demonstrated that a layer of compressive stress had a DOL of approximately 43.4 μm. The brush polishing process resulted in excess material removal from the major surface, leading to the layer of compressive stress being completely removed at a lateral distance of about 264 μm from a polished edge 602. As result, the polished edge 602 is completely devoid of compressive stress. The counterexamples were tested for edge strength using the apparatus 150 depicted in FIG. 5. A failure mode analysis revealed that the counterexamples failed as a result brushing defects on the edges or surfaces from the brush polishing process.

[0138] *Examples according to a first embodiment*

[0139] A first set of examples was prepared in accordance with the processes described herein. Workpieces were formed from fully chemically strengthened (DOL = 45 μm) Corning Gorilla™ Glass 3 having a 1.3 mm thickness and decorated with organic ink decorations. The workpieces had layers of compressive stress extending from each major surface with a similar DOC as those described above with respect to the counterexamples. The workpieces were separated from a strengthened sheet using laser nanoperforation followed by self-separation caused by the inherent stress in the ion-exchanged material. The workpieces so formed bear characteristically perpendicular edges and laser damage to the organic ink decorations bounded by part perimeter. FIG. 7 depicts an image of a portion of a workpiece 700 cut from a chemically strengthened glass sheet proximate to a boundary of an ink decoration 702. Nanoperforations were formed using a pulsed laser along a contour line disposed proximate (e.g., less than 150 μm) to the boundary of the ink decoration 702. As shown, laser-induced damage to the ink decoration 702 results in an as-cut boundary 704 disposed approximately 45 μm from an as-cut edge 706 of the workpiece 700. The laser-induced damage results in the as-cut edge 706 being relatively wavy such that the distance from the as-cut edge 706 substantially varies. As illustrated, the as-cut boundary 704 substantially varies from a linear shape. As shown, over a 1 mm segment of the as-cut boundary 704, peaks and valleys of the as-cut boundary 704 deviate from a line fit thereto by as much as 20 μm . If uncorrected, such a wavy boundary can result in inconsistent amounts of light leakage (e.g., when the substrates are used as a cover glass for a light source such as a display), which can adversely affect appearance.

[0140] After near-net shaping, the workpieces were stacked in preparation for brush polishing using single sheets of highly absorbent blue cleanroom paper as interposers. Brush polishing is then conducted using the following process conditions:

- 36mm brush filament length – potted 5mm deep into base portion of brush;
- 0.200mm individual brush filament diameter with filled resin construction;
- Spiral brush filament design with standard 33 winds;
- $\leq 100\mu\text{m}$ interposer thickness (single sheet of cleanroom paper) with uniform 1mm edge ingress;
- Calcined cerium oxide slurry (MIREK HL-05 slurry with d50 particle size of 1 μm and d95 of 3 μm)
- Brush speed 800 - 1000 rpm (292mm diameter cylindrical brush);
- Brush engagement 15 mm;
- $\leq 27.5\text{mm / min}$ feed rate; and

- $1 \leq$ brush polishing cycles.

[0141] As indicated by the above parameters, to provide the first set of examples, aggressive brush engagement was performed, with the workpieces being separated from one another by less than half of the filament diameter. This combination of interposer thickness and filament diameter resulted in concentrated contact between the brush filaments and the as-cut edge 706. Samples were formed with 2 polishing passes (also referred to as “BP cycles” herein), 3 polishing passes, and 6 polishing passes. Results for some of the examples (one at each of the number of polishing passes) are depicted in FIG. 8. As shown, a first substrate 800 was formed with 2 polishing passes and comprised a first polished edge 802. A second substrate 804 was formed with 3 polishing passes and comprised a second polished edge 806. A third substrate 808 was formed with 6 polishing passes and comprised a third polished edge 810.

[0142] The distances in FIG. 8 represent the first and second maximum linear dimensions 64 and 74 described herein with respect to FIGS. 1A-1C. Generally, examples fabricated with two polishing passes resulted in material removal of less than 100 μm at the major surfaces of the workpieces. Examples fabricated with three polishing passes resulted in material removal of less than 120 μm at the major surfaces of the workpieces. Examples fabricated with six polishing passes resulted in material removal of less than 160 μm at the major surfaces of the workpieces. This is far less than material removal than in the counterexamples. It is believed that such limited material removal from the major surfaces results in layers of compressive stress being present at the first, second, and third polished edges 802, 806, and 810.

[0143] The examples formed using the brush polishing processes described herein also exhibit crisp decoration boundaries. FIG. 9 depicts an image of a portion of a substrate 900 cut and polished from a chemically strengthened glass workpiece in accordance with the processes described herein. The substrate 900 includes a polished edge 902 and a decorative layer 904 with a polished decoration boundary 906. The polished decoration boundary 906 is sharper and crisper as compared to the as-cut boundary 704 described with respect to FIG. 7. As shown, over a 1 mm segment of the polished decoration boundary 906, peaks and valleys of the polished decoration boundary 906 deviate from a line fit thereto by no more than 10 μm . This is a result of interactions between the decorative layer 904 and the polishing material described herein.

[0144] Mechanical edge strength measurements were conducted and first set of examples. For comparison, another set of counter examples were formed from glass cut from

the same glass sheet and subjected to same chemical strengthening processes, but stacked with three times the interposer thickness (three pieces of cleanroom paper were used), such that the workpiece separation was greater than the brush filament diameter. Each substrate was strengthened under a partial IOX condition (2 hour immersion time) and a full IOX condition (4 hour immersion time). The results are depicted in FIG. 10. FIG. 10 includes images of a first counterexample 1002 and a second counterexample 1004. FIG. 10 also includes images of a first example 1006 and a second example 1008. As shown, the 3X interposer thickness resulted in more material removal at the corners of the workpieces, resulting in compressive stress layers being removed from the polished edges. Examples fabricated in accordance with the present disclosure, however, resulted in preservation of the compressive stress layers on the polished edges. Weibull distributions of mechanical edge strength values for the examples and counterexamples with each IOX treatment are also provided. As shown, the counterexamples each exhibit a B10 value that is less than 400 MPa, whereas each of the examples exhibit a B10 value greater than 600 MPa. The results were consistent irrespective of ion exchange treatment. This demonstrates that brush polishing using the methods described herein results in significant improvements in mechanical edge strength of chemically strengthened parts.

[0145] *Examples according to a second embodiment*

[0146] A second set of examples was prepared in accordance with the processes described herein. Workpieces were formed from fully chemically strengthened (DOL = 45 μm) Corning Gorilla™ Glass 3 having a 1.3 mm thickness and decorated with organic in decorations. The workpieces had layers of compressive stress extending from each major surface with a similar DOC as those described above with respect to the counterexamples. The workpieces were separated from a strengthened sheet using laser nanoperforation followed by self-separation. Brush polishing is then conducted using similar process conditions as those described above with respect to the first embodiment, with exception that the interposer was applied in liquid form (e.g., by one of inkjet, roll coating, spray coating, screen printing, or other suitable technique) to have the exact dimensions associated with each workpiece. There was 0 mm of interposer ingress in the second embodiment. These interposers had a thickness that is greater than the d50 slurry grain size and less than or equal to 100 μm . The advantaged edge profile described herein with respect to FIGS. 1A-1C was achieved as well as a crisp decoration boundary for these interposer setups. These demonstrate that the advantaged edge profile can be achieved at a variety of interposer thicknesses within the ranges described herein. and with no edge ingress.

[0147] *Examples according to a third embodiment*

[0148] A third set of examples was prepared in accordance with the processes described herein. Workpieces were formed from fully chemically strengthened (DOL = 45 μm) Corning Gorilla™ Glass 3 having a 1.3 mm thickness and decorated with organic ink decorations. The workpieces had layers of compressive stress extending from each major surface with a similar DOC as those described above with respect to the counterexamples. The workpieces were separated from a strengthened sheet using laser nanoperforation followed by self-separation. The workpieces so formed bear characteristically perpendicular edges and laser damage to the organic ink decorations bounded by part perimeter. After near-net shaping, the workpieces were stacked in preparation for brush polishing using relatively thick interposers. Brush polishing is then conducted using the following process conditions:

- 36mm brush filament length – potted 5mm deep into base portion of brush;
- 0.200mm individual brush filament diameter with filled resin construction;
- Spiral brush filament design with standard 33 winds;
- $500\ \mu\text{m} \leq$ interposer thickness with uniform 5 mm edge ingress;
- Calcined cerium oxide slurry (MIREK HL-05 slurry with d50 particle size of 1 μm and d95 of 3 μm)
- Brush speed 800 - 1000 rpm (292mm diameter cylindrical brush);
- Brush engagement 2 to 5 mm;
- $\leq 27.5\text{mm} / \text{min}$ feed rate; and
- $1 \leq$ brush polishing cycles.

[0149] As shown, the third embodiment differs from the first and second embodiments in that the brush filament engagement was passive in that the engagement length was less than one fifth of the filament length. Such passive brush engagement results in very low brush force on the part edges, leading to concentrated contact on the as-cut edges. The relatively large gap between the parts caused by the thick interposers also reduces resistance to brush movement, thereby further reducing brush force. Samples fabricated according to this third embodiment exhibited the advantaged edge profile described herein with respect to FIGS. 1A-1C, as well as a smooth decoration boundary. These results demonstrate that the advantaged edge profile can be achieved using both active and passive brush engagement.

[0150] *Examples according to a fourth embodiment*

[0151] A fourth set of examples was prepared in accordance with the processes described herein. Workpieces were formed from fully chemically strengthened (DOL = 45

μm) Corning Gorilla™ Glass 3 having a 1.3 mm thickness and decorated with organic in decorations. The workpieces had layers of compressive stress extending from each major surface with a similar DOC as those described above with respect to the counterexamples. The workpieces were separated from a strengthened sheet using laser nanoperforation followed by self-separation. The workpieces so formed bear characteristically perpendicular edges and laser damage to the organic ink decorations bounded by part perimeter. After near-net shaping, the workpieces were stacked in preparation for brush polishing using single sheets of highly absorbent blue cleanroom paper as interposers. Brush polishing is then conducted using the following process conditions:

- 18-36mm brush filament length – potted 5mm deep into base portion of brush;
- ≤ 0.1 mm individual brush filament diameter with filled resin construction;
- Spiral brush filament design with standard 33 winds;
- 100 μm interposer thickness with uniform 1 mm edge ingress;
- Calcined cerium oxide slurry (MIREK HL-05 slurry with d50 particle size of 1 μm and d95 of 3 μm)
- Brush speed 800 - 1000 rpm (292mm diameter cylindrical brush);
- Brush engagement 7 to 24 mm;
- ≤ 27.5 mm / min feed rate; and
- $1 \leq$ brush polishing cycles.

[0152] As shown, the fourth embodiment differs from the first and second embodiments in that the brush filament engagement was passive in that the filament diameter for the brushes was less than or equal to 0.1 mm. Such passive brush engagement results in very low brush force on the part edges, leading to concentrated contact on the as-cut edges. Samples fabricated according to this fourth embodiment exhibited the advantaged edge profile described herein with respect to FIGS. 1A-1C, as well as a smooth decoration boundary. These results demonstrate that the advantaged edge profile can be achieved using both active and passive brush engagement. These embodiments did not even remove the compressive stress layers from the polished edges when the workpieces were only subjected to a partial chemical strengthening treatment, resulting in a depth of compression between 20 μm and 25 μm. Even with such a reduced depth of compression, the reduced brush filament stiffness caused by the reduced diameter reduces the risk of erosion of the compressive stress layers.

[0153] *Examples according to a fifth embodiment*

[0154] A fifth set of examples was prepared in accordance with the processes described herein. Workpieces were formed from fully chemically strengthened (DOL = 45 μm) Corning Gorilla™ Glass 3 having a 1.3 mm thickness and decorated with organic ink decorations. The workpieces had layers of compressive stress extending from each major surface with a similar DOC as those described above with respect to the counterexamples. The workpieces were separated from a strengthened sheet using laser nanoperforation followed by self-separation. The workpieces so formed bear characteristically perpendicular edges and laser damage to the organic ink decorations bounded by part perimeter. After near-net shaping, the workpieces were stacked in preparation for brush polishing. The interposer was applied in liquid form (e.g., by one of inkjet, roll coating, spray coating, screen printing, or other suitable technique) to have the exact dimensions associated with each workpiece. Brush polishing is then conducted using the following process conditions:

- 18 mm brush filament length – potted 5mm deep into base portion of brush;
- 0.2 mm individual brush filament diameter with filled resin construction;
- Spiral brush filament design with standard 33 winds;
- Interposer thickness greater than d50 grain size and less than 100 μm with no edge ingress;
- Calcined cerium oxide slurry (MIREK HL-05 slurry with d50 particle size of 1 μm and d95 of 3 μm)
- Brush speed 800 - 1000 rpm (292mm diameter cylindrical brush);
- Brush engagement 7 mm;
- $\leq 27.5\text{mm} / \text{min}$ feed rate; and
- $1 \leq$ brush polishing cycles.

[0155] As shown, the fifth embodiment involved very aggressive brush engagement due to the reduced filament length when compared to the first embodiment. This reduced length increased the stiffness of the filaments. The very narrow interposers with no ingress further protect the peripheral regions of the major surfaces, facilitating such aggressive material removal. These examples exhibited the advantaged edge profile described herein with respect to FIGS. 1A-1C, as well a smooth decoration boundary.

[0156] *Examples according to a sixth embodiment*

[0157] Examples according to the sixth embodiment were formed under brush polishing conditions similar to those discussed with respect to the first embodiment. In the sixth embodiment, the workpieces were not chemically strengthened, but instead mechanically

strengthened by forming a glass-on-glass laminate with a core glass layer 1100 centrally disposed between two cladding glass layers 1102 (See FIG. 11A) having different coefficients of thermal expansion, such that the core layer is under tensile stress and the cladding layers are under compressive stress. The core glass layer 1100 comprised a core thickness of 600 μm and the cladding glass layer 1102 comprised a cladding thickness of 50 μm . The core glass layer 1100 had a CTE of 84.7 ppm/ $^{\circ}\text{C}$, while the cladding glass layers 1102 had a CTE of 34.3 ppm/ $^{\circ}\text{C}$ to form compressive stress therein. FIG. 11A depicts an image of an as-cut workpiece. FIG. 11B depicts the workpiece after polishing with six polishing passes, such that approximately 77 μm of material was removed from as-cut edges of the workpiece. As shown, the cladding layers 1102 were not fully removed from the polished sample at a polished edge 1104 thereof, so the compressive stress was preserved throughout the major surfaces. Mechanical edge strength of an as-cut workpiece and a polished substrate prepared according to the sixth embodiments was measured using the apparatus 150 described herein with respect to FIG. 5. Weibull distributions are shown in FIG. 11C. The as-cut workpieces exhibited a B20 value of about 216.7 MPa, whereas the polished sample exhibited a B20 value of about 364.7 MPa. These results demonstrate the efficacy of the methods described herein of restoring mechanical strength of cut parts for substrates strengthened using a variety of methods.

[0158] Referring now to FIG. 15, examples according to the present disclosure were tested for edge impact strength using a pendulum apparatus, such that a weight impacted an edge of a major surface of polished examples at an angle of 9° . Impact energy was varied by altering the drop position of the weight on the pendulum. Impact energy was increased until breakage was observed. The results are depicted in FIG. 12. The examples on the right were subject to partial ion exchange treatment, while the others were subjected to a full ion exchange treatment. As shown, the fully ion exchanged sample sets are at least as resistant to controlled edge impact as the partially ion exchanged sample set.

[0159] The previous six example embodiments utilized brush polishing on workpieces included printed ink decorations disposed thereon. The use of brush polishing on such workpieces is preferred due to the ability to achieve a crisp decoration boundary after the decoration boundary is damaged during near-net shaping (*see e.g.*, FIG. 7). Directing the polishing slurry flow to the interstitial regions between workpieces allows damaged portions of the ink decorations to be uniformly removed around the periphery of the part, resulting in a crisp decoration boundary. FIG. 13 is an image of a polished decorated sample 1300. The decorated sample 1300 has a polished edge 1302 and exhibits the advantaged edge profile described herein. Moreover, a decoration layer 1304 is disposed on a major surface of the

decorated sample 1300. The decoration layer 1304 was subjected to one of the brush polishing processes described herein so that a portion of the decoration layer 1304 was removed via a polishing slurry flow. As shown, the decoration layer 1304 includes a decoration boundary 1306 that is crisp and uniform as compared to that shown in FIG. 7. The decoration boundary 1306 is generally parallel to the polished edge 1302, resulting in an aesthetically pleasing appearance. Other polishing modalities, such as polishing wheels, generally do not achieve such crisp decoration boundaries.

[0160] Even abradable fixed abrasive polishing wheels such as those advocated in US 10,173,916 B2 contain diamond abrasive particles exceeding 10 μ m in size, making final edge flaws significantly larger than 2 μ m. Even if polishing by such modalities can achieve an edge profile having the shape described here, such substrates are disadvantaged to those described herein because they include flaws that are much deeper and wider than brush marks associated with the brush polishing processes described herein. Such methods are also difficult to control in terms of the extent of edge chamfering. The inconsistency of abrasive polishing wheels may lead to lower material utilization and reduced edge strength.

[0161] In some embodiments, interposers of the present disclosure may be used to apply, or assist in applying, decorations to substrates. For example, an interposer of the present disclosure may have an electronic device layer, or other desired decoration or layer, affixed thereto with a reverse configuration. The device layer or other decoration or layer may be configured to be transferrable, such that the decoration or layer may transfer from the interposer onto a substrate when the substrate is arranged in contact with the interposer. In some embodiments, the compressive force applied to a stack of substrates and interposers may help to transfer the decoration or layer from the interposer onto the substrate. In some embodiments, an adhesive layer may be applied between the decoration and substrate.

[0162] Simultaneous edge shaping and polishing processes of the present disclosure may additionally provide for a substantial time savings over conventional forming and finishing processes. That is, rather than a series of mechanical grinding steps to remove edge material and a series of polishing steps to remove flaws inflicted from the grinding, the single-stage brushing step described above may provide for a less time-consuming and less labor-intensive process.

[0163] It is to be appreciated that the processes described herein may provide for replacement of conventional mechanical near-net shaping and edge finishing with a single step, semi-batch brush polishing process that simultaneously forms and finishes thin glass edges. The above solutions represent a larger opportunity to deploy a superior finishing process

technology across numerous projects. This may be particularly seen with respect to automotive interior products. For example, finished thin glass product edge quality specifications for automotive interior products may be particularly demanding, requiring an edge strength of up to 215 MPa prior to chemical strengthening. Such a mechanical edge strength has been calculated to require maximum flaws post grinding not to exceed 11 microns, for example. A consequence of this is that manufacturing lines are now undergoing installation and commissioning that are not capable of meeting commercial and/or cost model objectives for edge finished thin glass products. Additionally, some manufacturers and industries have shown an increasing demand for thin glass parts that can be cold formed; such capability requires relatively high edge strength, which may be higher than can be achieved by conventional mechanical edge grinding followed by chemical strengthening.

[0164] While the edge forming and finishing processes described herein may be used in place of conventional grinding steps, it may further be appreciated that brushing processes described herein may be used in combination with substrate edge grinding in some embodiments. For example, a near-net shaped substrate may have edges formed by one or more mechanical grinding steps, after which the substrate may be arranged between interposers and subject to a brushing process described herein to polish edges to achieve a desired edge strength. Mechanical grinding may be performed using an abrasive grinding medium having a suitable abrasive size. Additionally, edge forming and finishing processes described herein may be used in place of, or in combination with, chemical edge strengthening processes such as, but not limited to, HF treatment and ion exchange treatment.

[0165] Forming and finishing processes of the present disclosure may additionally provide for more efficient and cost-effective manufacturing. In particular, a plurality of substrates, including tens or even hundreds of substrates, may be arranged in a stack with an interposer arranged between each substrate. The stack of substrates may be formed and finished together using the brushing processes described herein. Thus, processing time may be reduced to less than 10 minutes, less than 5 minutes, or less than 3 minutes per part. Additionally, processes of the present disclosure may have lower material waste as compared with conventional forming and finishing processes. In particular, brush polishing may achieve a desired edge shape and polish with less material removal than may be needed with a conventional grinding process. Moreover, processes of the present disclosure may provide for improved processing efficiency by allowing for edge forming and finishing to be performed on substrates after application of inks, devices, films, and/or other decorations. By applying decorations prior to edge forming and finishing, process time may be reduced dramatically.

Forming and finishing processes of the present disclosure may also be versatile in that such processes may be applied to a relatively wide variety of substrate materials, including for example, laminate materials and chemically strengthened materials, both of which may present challenges for conventional forming and finishing processes.

[0166] A number of embodiments are described in the following paragraphs to provide some examples of manufacturing processes of the present disclosure. It is to be appreciated that the following embodiments are provided as examples, and the application is not limited to the following embodiments.

[0167] In at least one embodiment of the present disclosure, strengthened or laminated thin glass articles or other substrates may be prepared by a range of near-net shaping technologies, including but not limited to, those listed above. The strengthened or laminated thin glass substrates or other substrates may have edges simultaneously formed to a desired edge profile and polished to a high-quality edge finish with characteristically low residual damage and flaw distribution and therefore high mechanical edge strength by the processes described herein.

[0168] In at least one embodiment of the present disclosure, strengthened and decorated thin glass substrates or other substrates prepared by decoration via screen printing of multiple parts on a full sheet with fiducials applied to enable picosecond laser cutting (nanoperforation followed by self-separation) may have edges simultaneously formed to a desired edge profile and polished to a high-quality edge finish with characteristically low residual damage and flaw distribution and therefore high mechanical edge strength by the processes described herein.

[0169] In at least one embodiment of the present disclosure, strengthened and subsequently over-decorated thin glass substrate or other substrates prepared by decoration via screen printing of multiple parts on a full sheet with fiducials applied to enable picosecond laser cutting (nanoperforation followed by self-separation) may have edges simultaneously formed to a desired edge profile and polished to a high-quality edge finish with characteristically low residual damage and flaw distribution and therefore high mechanical edge strength by processes described herein. Strategic interposers may be positioned between the substrates in such a way as to simultaneously allow removal by polishing a section of surface over-decoration thereby forming the decoration boundary instead of just preserving an existing one.

[0170] In at least one embodiment of the present disclosure, substrate edges may be formed and finished using mechanical slurry particles. A suitable mechanical slurry may be or include the DND Nanodiamond slurry product portfolio (includes DIA-SOL HL product name

and brand) manufactured for and distributed by Fujimi Corporation – these slurries are produced in concentrated (50 ct/liter) form and in a wide range of particle sizes (30nm - 75µm) and types (friable, metal bond). Other suitable mechanical slurry particles may be used additionally or alternatively. The slurry is dispensed in its most concentrated form (e.g., 50 ct/liter) for maximum efficiency, however dilution with water may be practiced as desired. The mechanical slurry particles may be readily rinsed clean after brushing.

[0171] In at least one embodiment of the present disclosure, brush polishing may be performed using interposers having a transferrable pattern (e.g., decal), enabling edge finishing to be conducted while the pressure used to restrain the stack is used to simultaneously transfer the pattern on the interposer onto a surface of the thin glass substrates. For example, a stack may be produced composed of alternating substrates and interposers. The interposers may be strategically positioned to control exposure of the edge to be polished to the polishing medium(s) and slurry(ies). The interposers may be designed with a combination of desired mechanical (relative dimensions, edge profile, compressibility, slip-stick coefficient, coefficient of thermal expansion, abrasion resistance, static charge), chemical (polishing slurry resistance, alkalinity resistance), electrical (static charge), and/or magnetic material properties. The interposers may additionally each have a transferrable decoration material arranged thereon and configured for activation by contact and pressure, such that during restraint by compression and brush polishing, desired decoration patterns may be transferred to the substrates being polished. The stack may be restrained via simple prolonged mechanical compression. The substrate edges may be subjected to a brush polishing process in which cylindrical brushes composed of engineered filaments of small ($\leq 0.200\text{mm}$) diameter and a range of lengths fastened together in bundles or “tufts” of a range of sizes (e.g., 3-5mm), patterns (e.g., spiral, staggered, straight), and/or brush densities are rotated at prescribed speeds (10 – 1000 rpm) and contacted with continuous streams of polishing slurry in a programmed set of operating motions. The filaments may be brought into controlled contact with the engineered stack of substrates. The substrates may be polished until residual subsurface damage from near-net shaping is reduced to characteristic maximum flaw size < 2 microns and the desired edge profile is imposed. The substrates may be further polished via subsequent brush polish step(s) with engineered finer polishing slurries employing separate brushes thereby further reducing residual subsurface damage. The substrates may be further chemically strengthened by exposure to HF and/or ion exchange.

[0172] In at least one embodiment, a brushing process of the present disclosure may provide for reduced polishing cycle time, as compared with conventional polishing operations.

For example, a brush may be operated to have a smooth polar polishing motion along an edge of the substrate stack, without intentional dwelling of polishing pressure and/or time on substrate corners or other edge features. In this way, a brush of the present disclosure may be continuously moved along a substrate perimeter edge with a constant or near constant linear speed (e.g., between 5-100 mm / min, or another suitable speed). It is to be appreciated that without corner or other feature dwelling or rounding motions, typical of conventional brushing operations, brush polishing operations of the present disclosure may be performed with reduced pass cycle times. Such compact polar polishing passes may be repeated to achieve a relatively high resolution.

[0173] In at least one embodiment, an interposer of the present disclosure may be or include one or more magnetically active materials. Moreover, in some embodiments, endcaps or chucks arranged at each end of the part stack may be configured to provide an electrostatic force. Together, the electrostatic endcaps and magnetic interposers may operate to maintain alignment of the interposers and substrates during brush processing. In some embodiments, this may be used to maintain alignment instead of, or in addition to, a compressive force applied to the stack.

[0174] As used herein, the terms “substantially” or “generally” refer to the complete or nearly complete extent or degree of an action, characteristic, property, state, structure, item, or result. For example, an object that is “substantially” or “generally” enclosed would mean that the object is either completely enclosed or nearly completely enclosed. The exact allowable degree of deviation from absolute completeness may in some cases depend on the specific context. However, generally speaking, the nearness of completion will be so as to have generally the same overall result as if absolute and total completion were obtained. The use of “substantially” or “generally” is equally applicable when used in a negative connotation to refer to the complete or near complete lack of an action, characteristic, property, state, structure, item, or result. For example, an element, combination, embodiment, or composition that is “substantially free of” or “generally free of” an element may still actually contain such element as long as there is generally no significant effect thereof.

[0175] To aid the Patent Office and any readers of any patent issued on this application in interpreting the claims appended hereto, applicants wish to note that they do not intend any of the appended claims or claim elements to invoke 35 U.S.C. § 112(f) unless the words “means for” or “step for” are explicitly used in the particular claim.

[0176] Additionally, as used herein, the phrase “at least one of [X] and [Y],” where X and Y are different components that may be included in an embodiment of the present

disclosure, means that the embodiment could include component X without component Y, the embodiment could include the component Y without component X, or the embodiment could include both components X and Y. Similarly, when used with respect to three or more components, such as “at least one of [X], [Y], and [Z],” the phrase means that the embodiment could include any one of the three or more components, any combination or sub-combination of any of the components, or all of the components.

[0177] In the foregoing description various embodiments of the present disclosure have been presented for the purpose of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise form disclosed. Obvious modifications or variations are possible in light of the above teachings. The various embodiments were chosen and described to provide the best illustration of the principals of the disclosure and their practical application, and to enable one of ordinary skill in the art to utilize the various embodiments with various modifications as are suited to the particular use contemplated. All such modifications and variations are within the scope of the present disclosure as determined by the appended claims when interpreted in accordance with the breadth they are fairly, legally, and equitably entitled.

Claims

What is claimed is:

1. A glass article comprising:
 - a first major surface;
 - a second major surface disposed opposite the first major surface; and
 - a polished edge extending between the first major surface and the second major surface, wherein:
 - the polished edge comprises at least one of: (a) an Ra surface roughness that is greater than or equal to 1 nm and less than or equal to 20nm; (b) a root mean squared surface roughness that is greater than or equal to 1 nm and less than or equal to 30 nm; and (c) a peak to valley surface roughness that is greater than or equal to 10 nm and less than or equal to 50 nm,
 - the glass article is chemically strengthened such that the glass article comprises a first layer of compressive stress extending from the first major surface to a first depth of compression (DOC_1) and a second layer of compressive stress extending from the second major surface to a second depth of compression (DOC_2), wherein a majority of the polished edge is not under compressive stress, and
 - at least one of the first layer of compressive stress and the second layer of compressive stress extends to the polished edge.
2. The glass article of claim 1, wherein:
 - the polished edge comprises a plurality of brush marks arranged thereon in a substantially parallel configuration, the brush marks imparted by a brush polishing process.
3. The glass article of any one of claims 1-2, wherein a plurality of the glass articles with the same composition, thickness, and chemical strengthening exhibit a Weibull distribution with a B10 value that is greater than or equal to 500 MPa, when tested for mechanical edge strength using a four-point bend test in accordance with ASTM C158-02.
4. The glass article of any one of claims 1-3, wherein the polished edge exhibits all of (a), (b), and (c).

5. The glass article of any one of claims 1-4, wherein:
the glass article comprises a maximum thickness (T) measured between major surfaces of the glass article, and
the polished edge comprises a length that is greater than $T - \text{DOC}_1 - \text{DOC}_2$.
6. The glass article of any one of claims 1-5, wherein, in a cross section of the glass article taken in a direction perpendicular to the polished edge and the first major surface, the first major surface comprises a first peripheral region where material of the glass article was removed from the first major surface during a brush polishing process, wherein the first peripheral region comprises a width measured in a direction perpendicular to the polished edge that is less than or equal to 200 μm .
7. The glass article of claim 6, wherein:
the first peripheral region comprises a curved region extending inward from the polished edge, wherein, within the cross-section, the polished edge transitions to the curved region at a boundary of an outer surface of the glass article, and
at the boundary, the outer surface exhibits a minimum radius of curvature that is greater than or equal to twice a maximum thickness of the glass article, as measured between the first major surface and the second major surface.
8. The glass article of claim 7, wherein the curved region comprises:
a width taken in the direction perpendicular to the polished edge that is less than or equal to $2 * \text{DOC}_1$, and
a depth taken in a direction perpendicular to the first major surface at a geometric center of the first major surface, the depth being less than or equal to $0.5 * \text{DOC}_1$.
9. The glass article of any one of claims 6-8, wherein, in the cross section, the second major surface comprises a second peripheral region where material of the glass article was removed from the second major surface during the brush polishing process.
10. The glass article of claim 9, wherein the first and second peripheral regions comprise different shapes such that the glass article comprises asymmetrical chamfers.

11. The glass article of any one of claims 1-10, further comprising an anti-reflective coating disposed on the first major surface, the anti-reflective coating comprising alternating layers of higher and lower refractive index materials, wherein a periphery of the first major surface exhibits a golden hue when viewed from normal incidence and illuminated with a diffuse D65 illuminate simulating ambient lighting conditions.

12. The glass article of any one of claims 1-11, wherein the first and second major surfaces are devoid of brush marks associated with a brush polishing process performed on the polished edge.

13. The glass article of any one of claims 12, wherein the first and second major surfaces comprise slurry flow lines, the slurry flow lines comprising a maximum width that is less than 3 μm .

14. The glass article of any one of claims 1-13, further comprising an ink layer disposed on the second major surface, the ink layer comprising an outer boundary offset from the polished edge by a distance of less than 160 μm measured perpendicular to the polished edge.

15. The glass article of claim 14, wherein the outer boundary comprises slurry flow lines from a flow of a polishing slurry associated with a brush polishing process, the slurry flow lines extending substantially parallel to the outer boundary.

16. A glass article comprising:
a first major surface;
a second major surface disposed opposite the first major surface; and
a polished edge extending between the first major surface and the second major surface, wherein:

the polished edge comprises at least one of: (a) an Ra surface roughness that is greater than or equal to 1 nm and less than or equal to 20nm; (b) a root mean squared surface roughness that is greater than or equal to 1 nm and less than or equal to 30 nm; and (c) a peak to valley surface roughness that is greater than or equal to 10 nm and less than or equal to 50 nm,

the glass article is chemically strengthened such that the glass article comprises at least a first layer of compressive stress extending from the first major surface to a first depth of compression (DOC_1),

in a cross section of the glass article taken in a direction perpendicular to the polished edge and the first major surface, the first major surface comprises a first peripheral region where material of the glass article was removed from the first major surface during a polishing process, wherein the first peripheral region comprises a depth measured in a direction perpendicular to the first major surface at a geometric center of the first major surface, wherein the depth is less than or equal to $0.5 * DOC_1$ such that a portion of the polished edge is under compressive stress, wherein a majority of the polished edge is not under compressive stress.

17. The glass article of claim 16, wherein the first peripheral region comprises a width measured in a direction perpendicular to the polished edge that is less than or equal to $200\ \mu\text{m}$.

18. The glass article of claim 17, wherein the width is less than or equal to $2 * DOC_1$.

19. The glass article any one of claims 16-18, wherein:

the first peripheral region comprises a curved region extending inward from the polished edge, wherein, within the cross-section, the polished edge transitions to the curved region at a boundary of an outer surface of the glass article, and

at the boundary, the outer surface exhibits a minimum radius of curvature that is greater than or equal to twice a maximum thickness of the glass article, as measured between the first major surface and the second major surface.

20. The glass article of any one of claims 16-19, wherein, in the cross section, the second major surface comprises a second peripheral region where material of the glass article was removed from the second major surface during the brush polishing process.

21. The glass article of claim 20, wherein the first and second peripheral regions comprise different shapes such that the glass article comprises asymmetrical chamfers.

22. The glass article of any one of claims 16-21, further comprising an anti-reflective coating disposed on the first major surface, the anti-reflective coating comprising alternating layers of higher and lower refractive index materials, wherein a periphery of the first major surface exhibits a golden hue when viewed from normal incidence and illuminated with a diffuse D65 illuminate simulating ambient lighting conditions.

23. The glass article of any one of claims 16-22, wherein:
the polished edge comprises a plurality of brush marks arranged thereon in a substantially parallel configuration, the brush marks imparted by a brush polishing process.

24. The glass article of claim 23, wherein the first and second major surfaces are devoid of the brush marks.

25. The glass article of claim 24, wherein the first and second major surfaces comprise slurry flow lines, the slurry flow lines comprising a maximum width that is less than 3 μm .

26. The glass article of any one of claims 16-25, further comprising an ink layer disposed on the second major surface, the ink layer comprising an outer boundary offset from the polished edge by a distance of less than 160 μm measured perpendicular to the polished edge.

27. The glass article of claim 26, wherein the outer boundary comprises slurry flow lines from a flow of a polishing slurry associated with a brush polishing process, the slurry flow lines extending substantially parallel to the outer boundary.

28. The glass article of any one of claims 16-27, wherein the polished edge exhibits all of (a), (b), and (c).

29. A method of finishing an edge surface of a strengthened glass substrate, the method comprising:

arranging the strengthened glass substrate between a first interposer and a second interposer;

applying a compressive force to the strengthened glass substrate and interposers; and

polishing an edge surface of the strengthened substrate by removing material of the strengthened glass substrate using a rotary brush and a polishing slurry flow, wherein the rotary brush comprises a plurality of brush filaments, wherein contact between the strengthened glass substrate and the rotary brush is concentrated on the edge surface of the substrate, wherein the polishing slurry flow is concentrated on major surfaces of the strengthened glass substrate.

30. The method of claim 29, wherein thicknesses of the first and second interposers are greater than a d50 grain size of the polishing slurry flow.

31. The method of any one of claims 29-30, wherein the polishing comprises at least two brush polishing passes.

32. The method of any one of claims 29-31, wherein at most 50 μm of the material of the strengthened glass substrate is removed from the edge surface during the polishing.

33. The method of any one of claims 29-32, wherein the material of the strengthened glass substrate is removed from peripheral portions of major surfaces of the strengthened glass substrate, the peripheral portions having widths that are less than or equal to 200 μm .

34. The method of claim 33, wherein, after the polishing, the peripheral portions have depths that are less than a depth of compression associated with a layer of compressive stress on one of the major surfaces.

35. The method of any one of claims 29-34, wherein each of the brush filaments comprise a filament diameter, wherein the first and second interposers comprise thicknesses that are less than that of the filament diameter to concentrate the contact on the edge surface.

36. The method of claim 35, wherein the filament diameter is less than half of the thicknesses of the first and second interposer.

37. The method of any one of claims 35-36, wherein:
the plurality of brush filaments comprise a filament length,
the brush filament diameter is greater than 0.1 mm, and
during the chamfering and polishing, the rotary brush is disposed a distance from the strengthened glass substrate such that at least one third of the filament length of the plurality of brush filaments engage with the edge surface.

38. The method of any one of claims 29-34, wherein:
the plurality of brush filaments comprise a filament length and a filament diameter, and
one of:

- (i) during the polishing, the rotary brush is disposed a distance from the strengthened glass substrate such that at less than one fifth of the filament length of the plurality of brush filaments engage with the edge surface, and
- (ii) the plurality of brush filaments comprise a filament diameter of less than or equal to 0.1 mm.

39. The method of claim 28, wherein the filament diameter is less than thicknesses of the first and second interposers.

40. The method of any one of claims 29-39, further comprising disposing an ink layer around a periphery of a major surface of the strengthened glass substrate prior to the polishing, wherein a portion of the ink layer is removed during the polishing by the polishing slurry flow.

41. The method of any one of claims 29-40, further comprising near-net shaping the strengthened glass substrate prior the polishing.

42. The method of claim 41, wherein the near-net shaping comprises forming nano-perforations along a contour line in the strengthened glass substrate using a pulsed laser beam and separating the strengthened glass sheet at the contour line via one of thermal separation or self-separation.

43. The method of any one of claims 29-42, wherein the strengthened glass substrate is a chemically strengthened glass substrate.

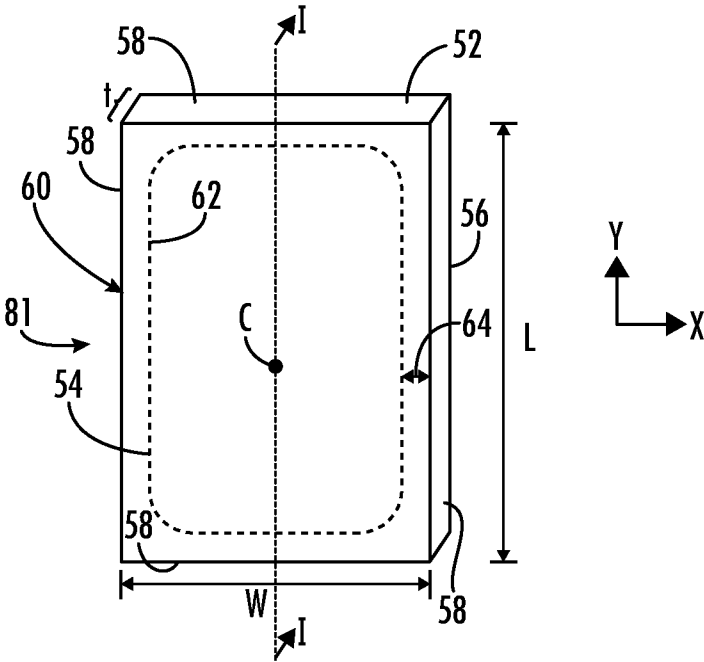


FIG. 1A

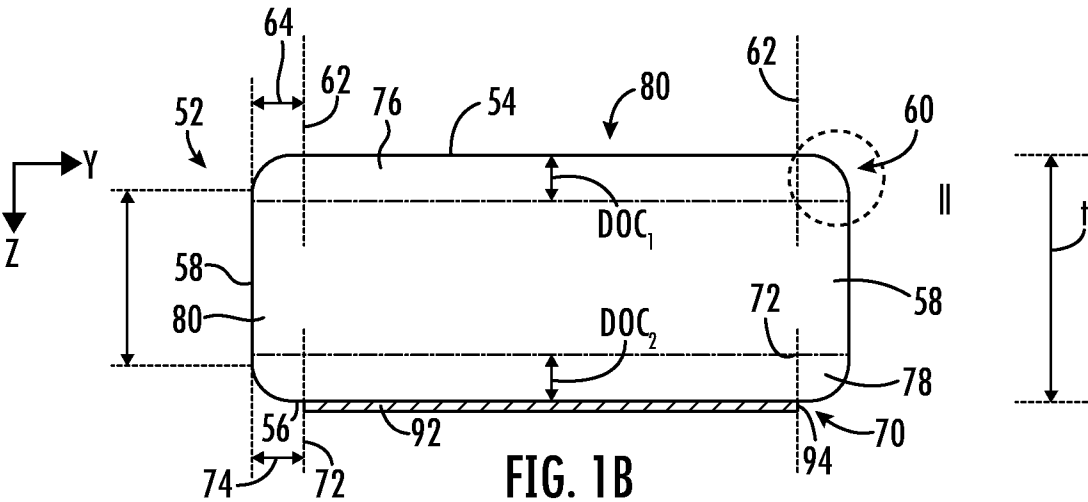


FIG. 1B

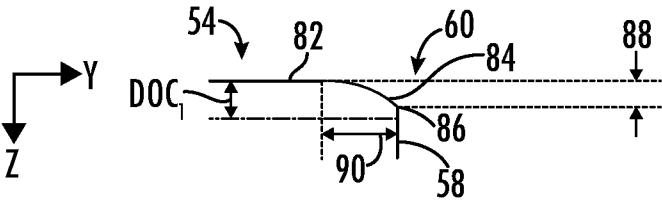


FIG. 1C

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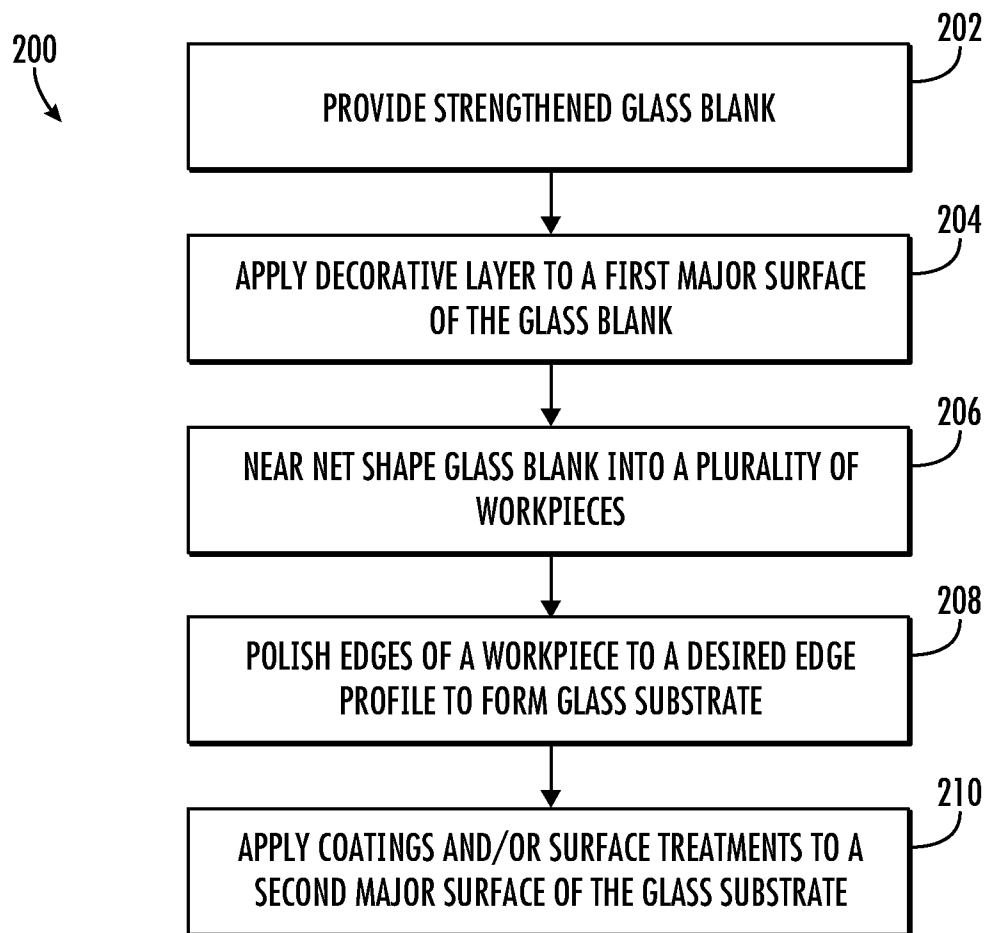


FIG. 2

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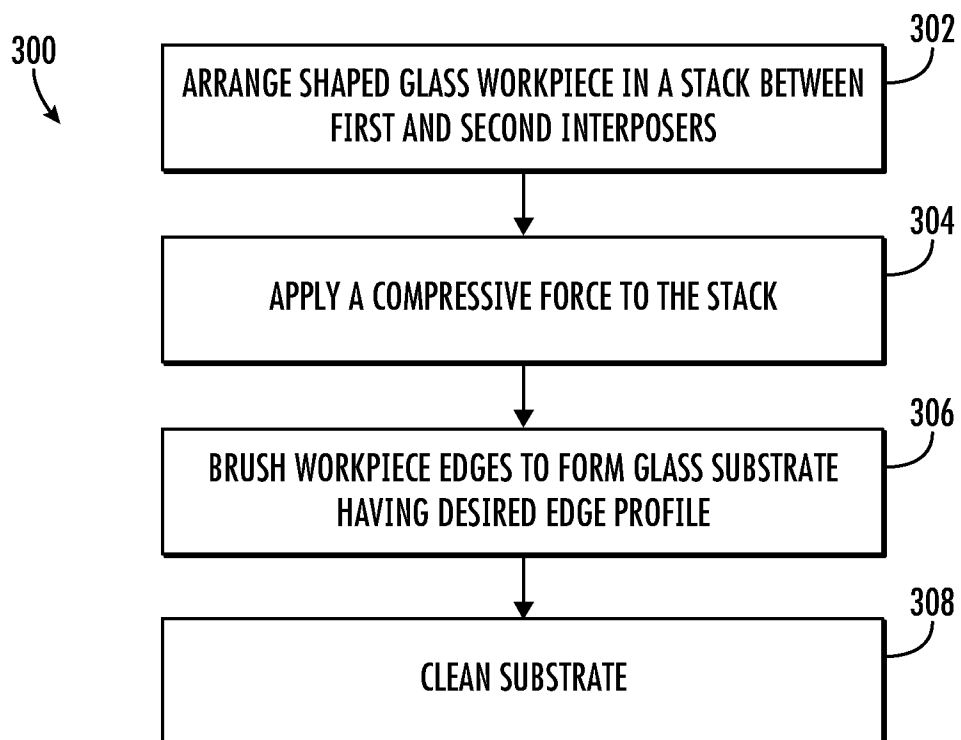


FIG. 3

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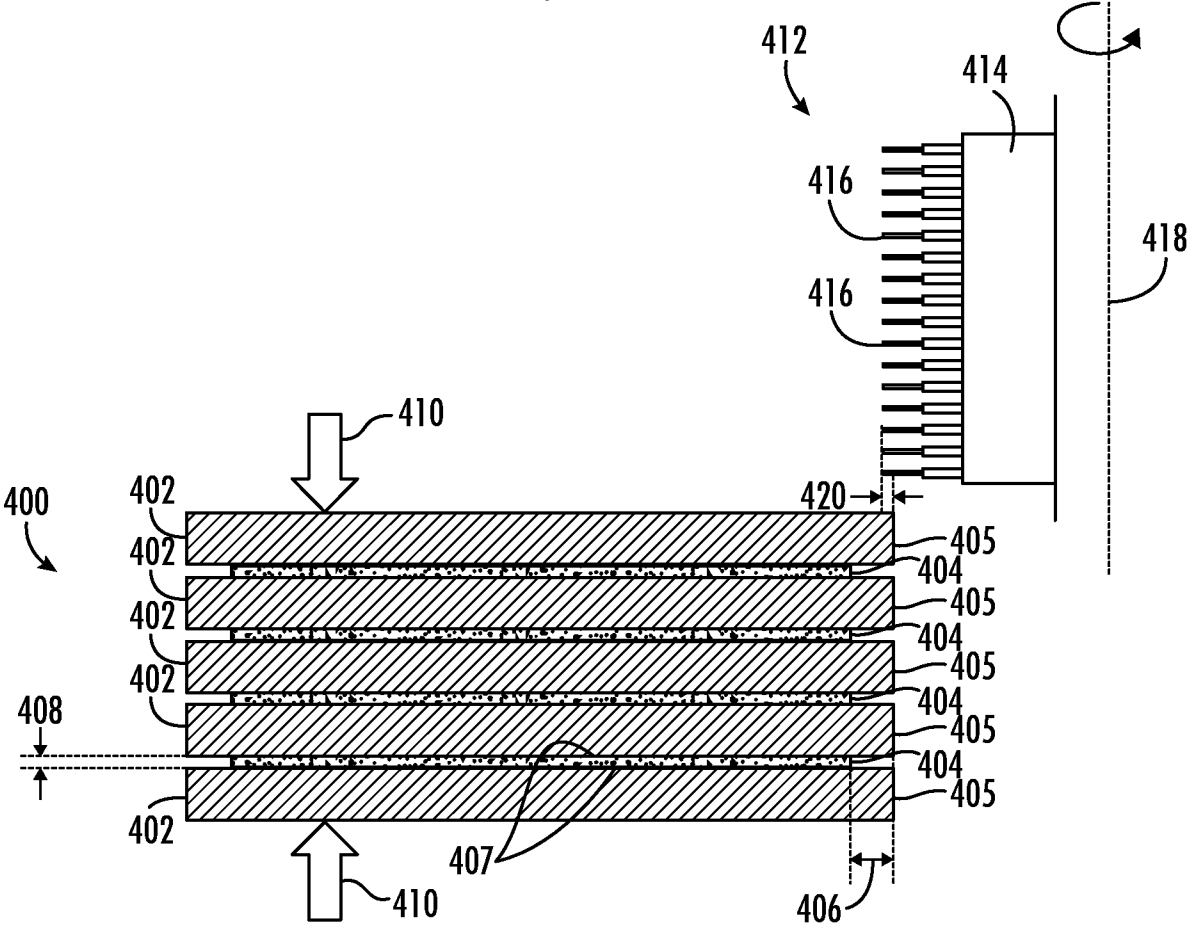


FIG. 4A

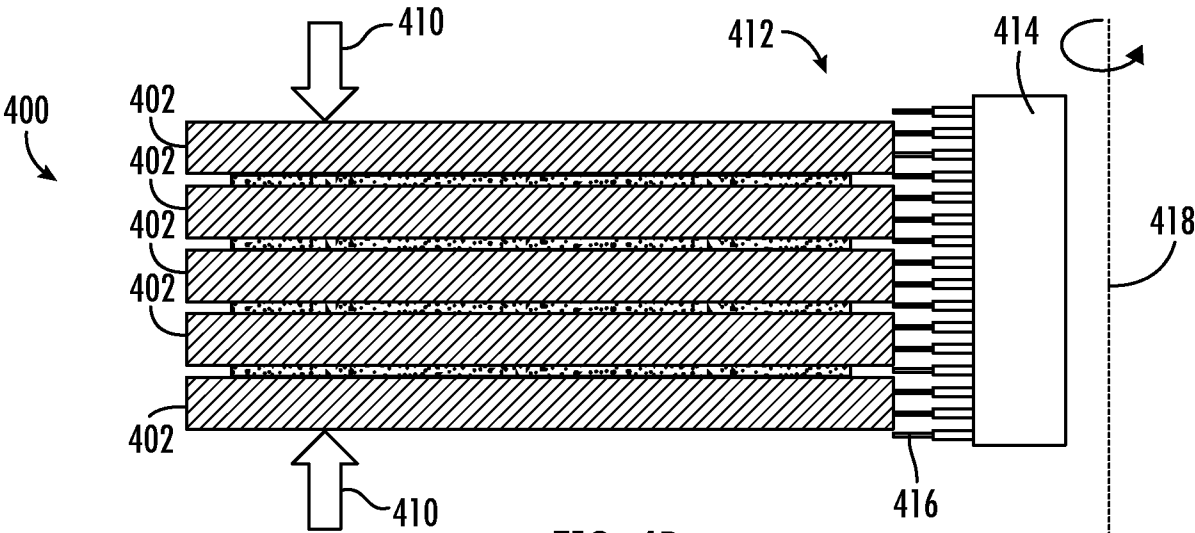


FIG. 4B

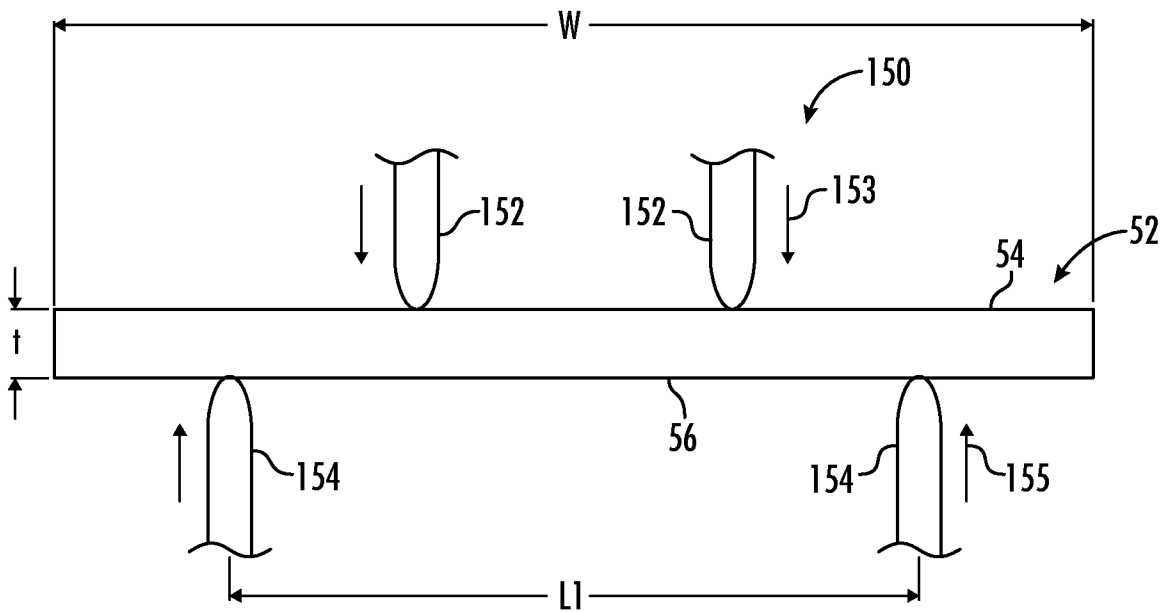


FIG. 5

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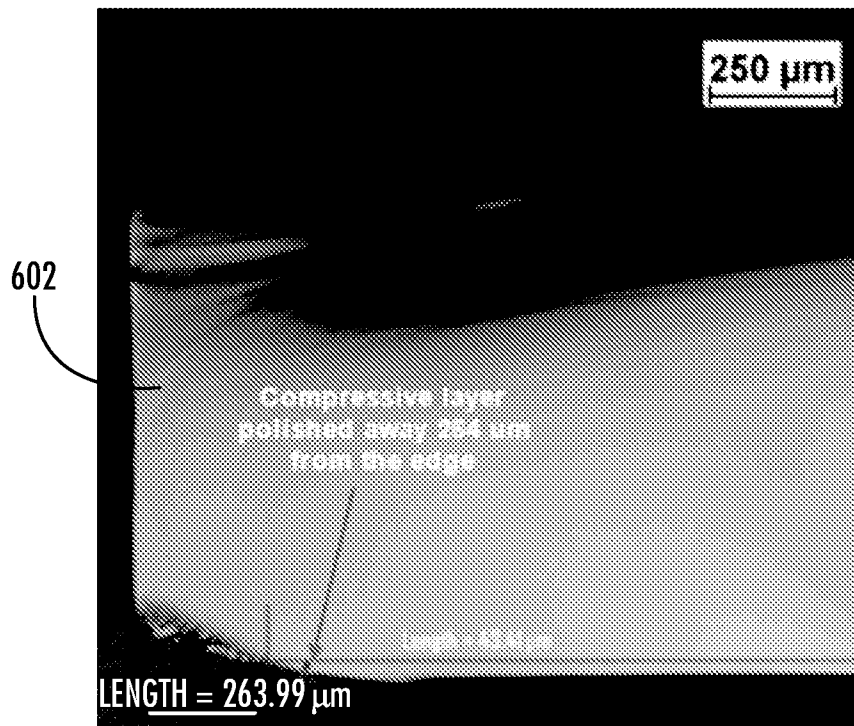


FIG. 6



FIG. 7

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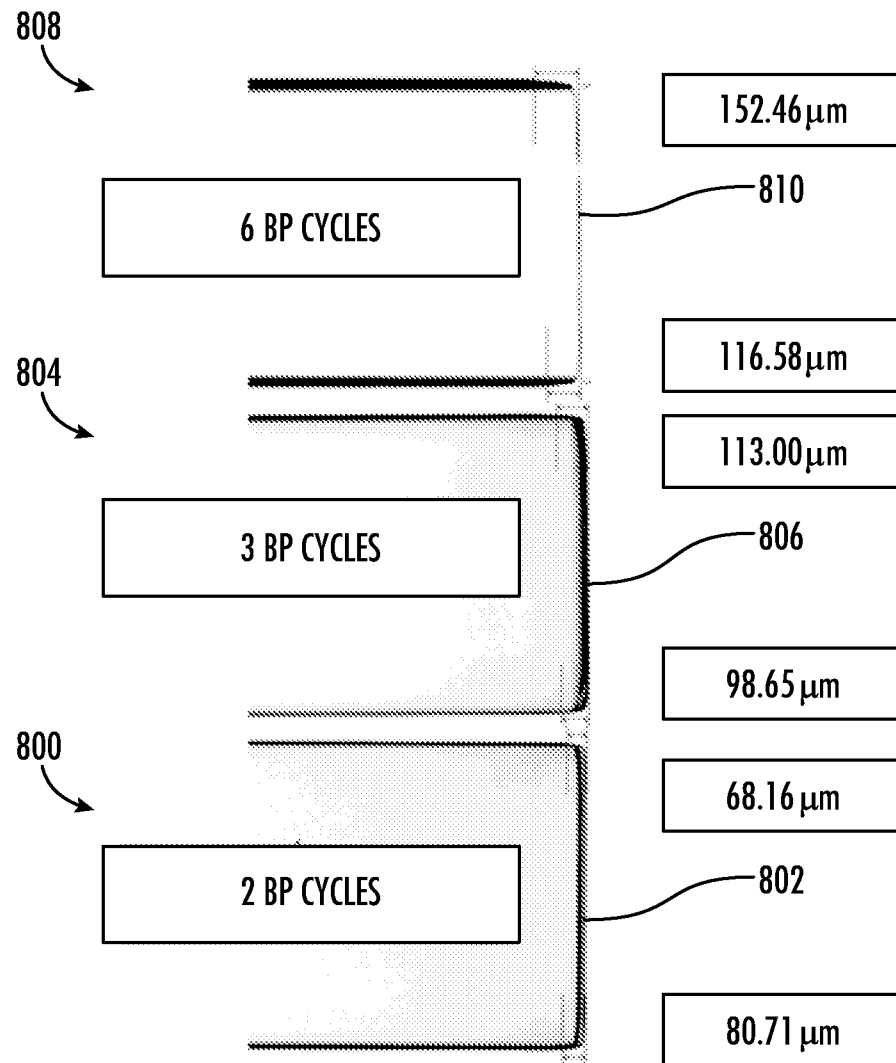


FIG. 8

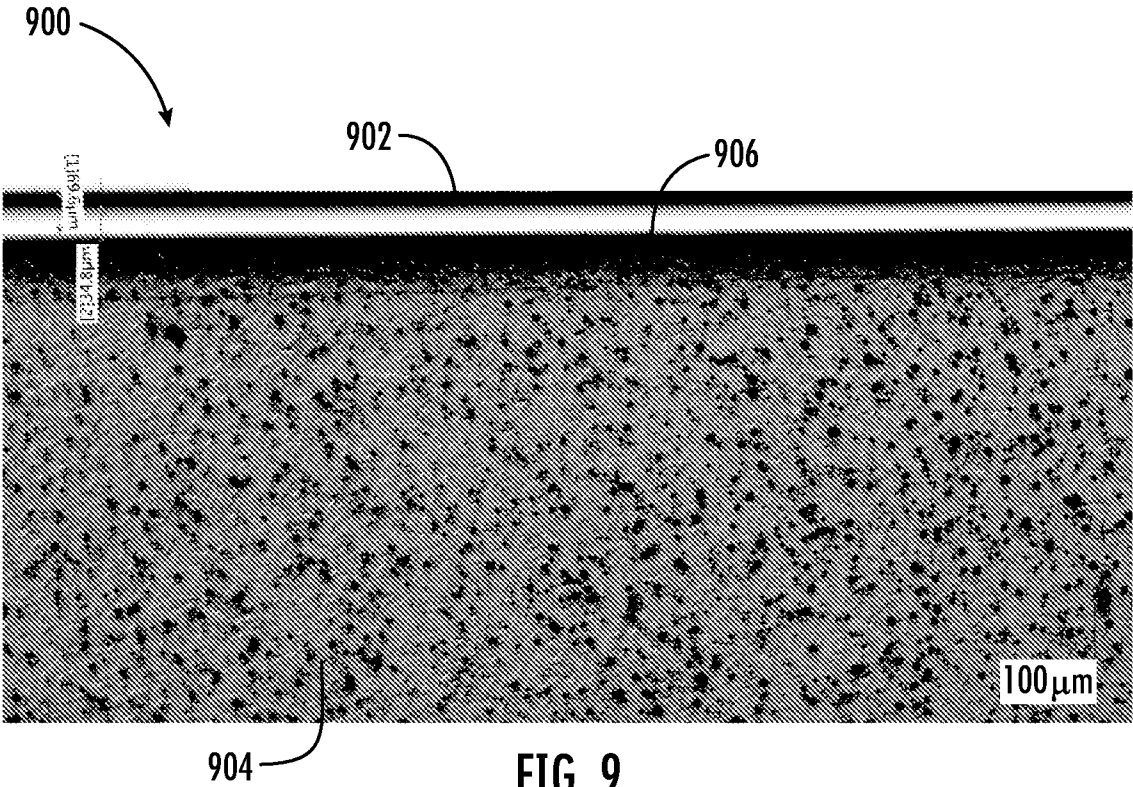


FIG. 9

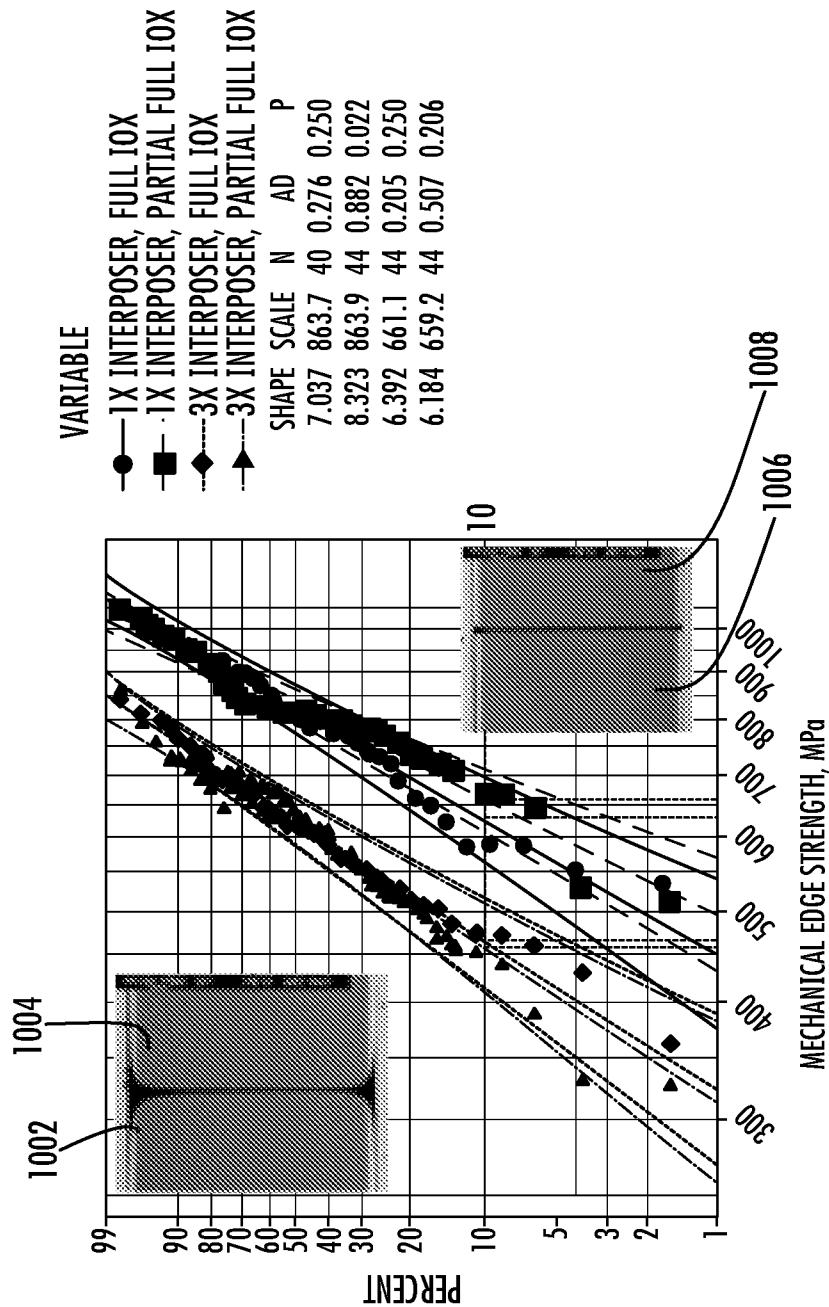


FIG. 10

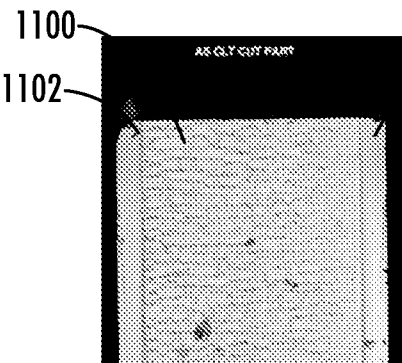


FIG. 11A

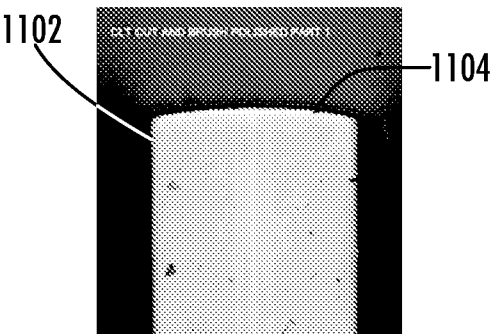


FIG. 11B

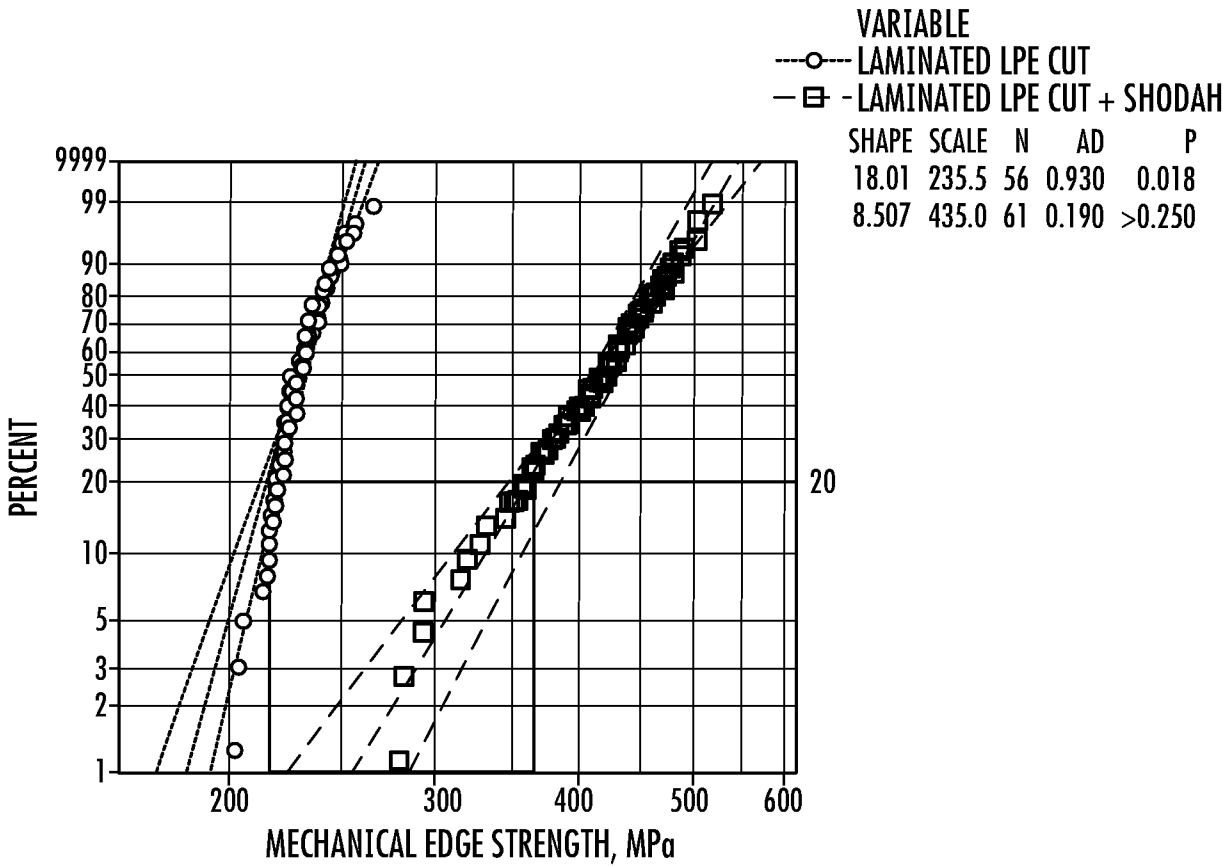


FIG. 11C

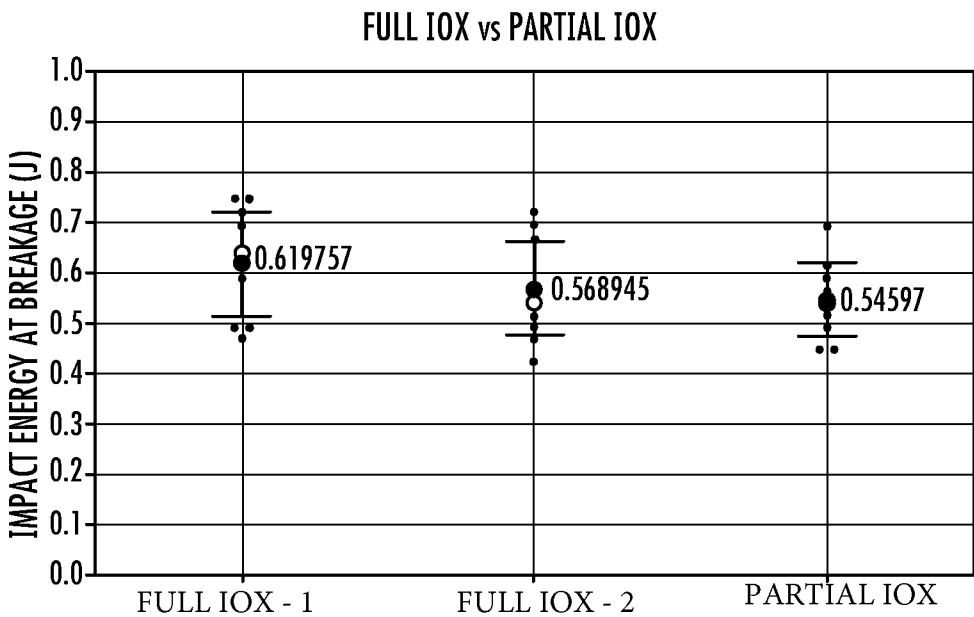


FIG. 12

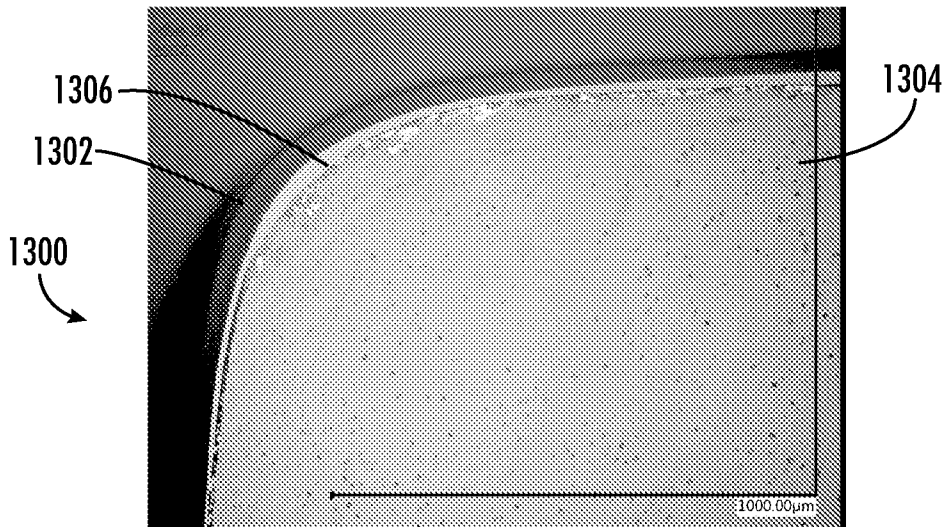


FIG. 13

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2024/031361

A. CLASSIFICATION OF SUBJECT MATTER INV. C03C21/00 B24B29/00 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) C03C B24D B24B		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2022/339751 A1 (BANKAITIS JONAS [US] ET AL) 27 October 2022 (2022-10-27) paragraphs [0008] - [0131]; claims; figures; examples -----	1 - 43
X	US 2014/170388 A1 (KASHIMA IZURU [JP] ET AL) 19 June 2014 (2014-06-19) paragraphs [0010] - [0100]; claims; figures; examples; tables -----	1 - 43
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 11 September 2024		Date of mailing of the international search report 26/09/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Wrba, Jürgen

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2024/031361

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