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(54) Title: LASER SCORING OF GLASS AT ELEVATED TEMPERATURES

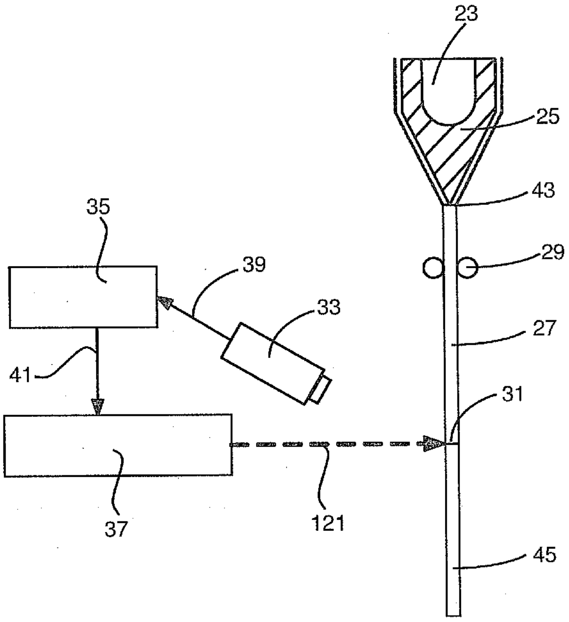

FIG. 8

(57) Abstract: Laser scoring of individual glass sheets (45, 112) and glass ribbons (27) at elevated temperatures is disclosed. A uniform vent can be created along an intended score line (31, 115) by heating a glass surface (114) with a laser beam (113) up to a temperature in a range whose lower limit (11) is defined by the stress required to maintain propagation of an initial flaw (111) to form the vent and whose upper limit (13) is equal to or less than the strain point of the glass. In certain embodiments, the glass temperature under the laser beam (113) stays within these limits regardless of the background temperature of the glass through the use of flexible laser power control provided by a controller (35) which causes a laser (37) to produce a laser power profile along the score line (31, 115) which varies inversely with the glass temperature gradient. The glass temperature gradient can, for example, be detected in real time using a detector (33), e.g., an infrared camera. By controlling the laser beam power in this way, process margins can be significantly increased during the scoring of individual glass sheets (45, 112) and glass ribbons (27) that exhibit significant glass temperature variations.

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LASER SCORING OF GLASS AT ELEVATED TEMPERATURES

[0001] This application claims the benefit of priority under 35 USC 119(e) of US Provisional Application Serial No. 61/181,473 filed on May 27, 2009.

Field

[0002] This disclosure relates to laser scoring of glass sheets and ribbons and, in particular, to laser scoring where part or all of the score line passes through glass that is at an elevated temperature, i.e., a temperature above room temperature.

DEFINITIONS

[0003] For ease of presentation, in the description that follows and in the claims, except where specifically indicated, the phrase "glass sheet" is used generically to refer to both an individual glass sheet and to a glass ribbon.

BACKGROUND

[0004] Scoring of glass is conventionally accomplished using mechanical tools. However, an alternative exists that uses laser radiation, e.g., CO_2 laser radiation at a wavelength of 10.6μm, to heat the glass and create tensile stress via a temperature gradient. The use of a laser for glass scoring is discussed in commonly-assigned U.S. Patent No. 5,776,220 entitled "Method and apparatus for breaking brittle materials" and U.S. Patent No. 6,327,875 entitled "Control of median crack depth in laser scoring," the contents of both of which are incorporated herein by reference in their entireties.

[0005] As shown in FIG. 9, during laser scoring, a median crack (also known as a partial vent or, simply, a vent) is created in a major surface 114 of a glass sheet 112 along a score line 115. In order to create the vent, a small initial flaw 111 is formed on the glass surface near one of its edges, which is then transformed into the vent by propagating laser light 121 formed into a beam 113 across the surface of the glass followed by a cooling area produced by a cooling nozzle 119. Heating of the glass with a laser beam and quenching it immediately thereafter with a coolant creates a thermal gradient and a corresponding stress field, which is responsible for the propagation of the initial flaw to form the vent.

[0006] The relationship between the laser beam 113 and the cooling area (quenching zone) is shown in more detail in FIG. 10, where the direction of propagation of the beam and cooling area relative to the glass surface is shown by the reference number 17. In this figure, the length of the laser beam on the surface of the glass is "b" and the separation between the trailing edge of the laser beam and the leading edge of the cooling area 15 is "L".

[0007] Among the challenges associated with laser scoring is the problem of residual stress in the glass sheet. Such stress is a particularly significant problem in the case of glass sheets that are to be used as substrates in display devices. Many display devices, such as TFT-LCD panels and organic light-emitting diode (OLED) panels, are made directly on glass substrates. To increase production rates and reduce costs, a typical panel manufacturing process simultaneously produces multiple panels on a single substrate or a sub-piece of a substrate. At various points in such processes, the substrate is mechanically divided into parts along cut lines.

[0008] Such mechanical dividing changes the stress distribution within the glass, specifically, the in-plane stress distribution seen when the glass is vacuumed flat. Even more particularly, the dividing relieves residual stresses in the sheet at the cut line since the cut edge is rendered traction free. Such stress relief in general results in changes in the vacuumed-flat shape of the glass sub-pieces, a phenomenon referred to by display manufacturers as "distortion."

[0009] Although the amount of shape change as a result of stress relief is typically quite small, in view of the pixel structures used in modern displays, the distortion resulting from mechanically dividing individual panels out of a larger sheet can be large enough to lead to substantial numbers of defective (rejected) displays. Accordingly, the distortion problem is of substantial concern to display manufacturers and specifications regarding allowable distortion can be as low as 2 microns or less.

[0010] The amount of distortion produced when such mechanical dividing is performed depends on the residual stress in the sheet, with lower levels of residual stress producing smaller distortions. Because laser scoring relies on heating the glass to produce a stress field, there is an inherent conflict between applying sufficient heat to produce enough stress to achieve a reproducible vent and yet not so much heat as to substantially increase the residual stress in the glass sheet being scored.

[0011] In addition to the distortion problem, residual stress is also important in terms of the quality of the edges produced when a laser-scored sheet of glass is divided into two sub-pieces. High levels of residual stress have been associated with edges having relatively low strength and poor quality, e.g., splinters and micro cracks. It has also been found that high residual stress nearby the glass edge may cause a gradual deterioration of the edge quality, namely chipping or delamination, which manifests itself some time after scoring or can be induced by an external impact.

[0012] Although laser scoring of glass has been the subject of substantial research and development efforts, to date, those efforts have been limited to scoring individual glass sheets where the sheets have been at room temperature. Moreover, the temperature distribution in the sheets has been uniform. Accordingly, the art is silent as to whether glass sheets having elevated temperatures and/or non-uniform temperature distributions can be successfully scored using a laser. Indeed, even the basic question as to whether laser beam power should be increased, decreased, or left the same when scoring is performed at elevated temperatures has not been answered.

[0013] Beyond this qualitative question, there is no quantitative information regarding the modifications that should be made to room temperature laser scoring when the glass sheet being scored is at an elevated temperature. Because laser scoring at elevated temperatures is important in such applications as separating individual glass sheets from a glass ribbon and/or trimming the edges (beads) of the separated individual sheets, the lack of quantitative information has restricted the use of laser scoring in the manufacture of glass sheets, such as the glass sheets used as substrates in display applications.

[0014] The present disclosure addresses this deficit in the art and, among other things, provides easy-to-use quantitative techniques for selecting laser beam power levels for any particular combination of scoring speed, scoring equipment (e.g., laser wavelength, laser beam size, laser beam shape, cooling area size, cooling area shape, cooling area temperature, laser beam-to-cooling area spacing, etc.), glass properties (e.g., thickness, CTE, Young's modulus, chemical composition, etc.), and glass temperatures and temperature distributions (e.g., uniform, linear, non-linear, and combinations thereof).

SUMMARY

[0015] A method is disclosed for scoring a glass sheet (27, 45, 112) along a score line (31, 115) using a laser beam (113) wherein for at least a portion of the score line (31, 115), the glass is above room temperature prior to application of the laser beam (113), the method including:

(a) translating a laser beam (113) along the score line (31, 115); and

(b) translating a cooling area (15) over the score line (31, 115) in tandem with the laser beam (113);

wherein heating by the laser beam (113) contributes to the formation of a vent in the glass sheet (27, 45, 112) and the power of the laser beam (113) is selected so that:

(i) the temperature of the glass surface (114) under the laser beam (113) is less than or equal to the glass' strain point; and

(ii) the laser beam's power satisfies the relationship:

$$0.85(\alpha - \beta T_{prior}(x)) \leq P(x) \leq 1.10(\alpha - \beta T_{prior}(x))$$

where x represents distance along the score line (31, 115), P(x) is the laser beam's power along the score line (31, 115), $T_{prior}(x)$ is the temperature of the glass in degrees centigrade along the score line (31, 115) prior to application of the laser beam (113), $T_{prior}(x) > 25°C$ for at least one value of x (e.g., $T_{prior}(x) \geq 60°C$ for at least one value of x), and α and β are positive constants.

[0016] Also, an apparatus is disclosed for scoring a glass sheet (27, 45, 112) along a score line (31, 115) which includes:

(a) a laser (37) which produces a laser beam (113);

(b) a detector (33) which detects the temperature of the surface (114) of the glass sheet (27, 45, 112) at at least one location; and

(c) a controller (35) operatively connected (39, 41) to the laser (37) and the detector (33), the controller (35) adjusting the power P of the laser beam (113) based on the temperature of the surface (114) of the glass sheet (27, 45, 112) detected by the detector (33) at the at least one location.

[0017] Further, an apparatus is disclosed for scoring a glass sheet (27, 45, 112) along a score line (31, 115) that includes:

(a) a laser (37) which produces a laser beam (113); and

(b) a controller (35) operatively (41) connected to the laser (37);

wherein:

(i) the controller (35) divides the score line (31, 115) into a plurality of segments, and

(ii) the controller (35) adjusts the target (specified) power of the laser beam (113) so that the target power is constant for each segment.

[0018] The reference numbers used in the above summaries of the various aspects of the disclosure are only for the convenience of the reader and are not intended to and should not be interpreted as limiting the scope of the invention. More generally, it is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention and are intended to provide an overview or framework for understanding the nature and character of the invention.

[0019] Additional features and advantages of the invention are set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. It is to be understood that the various features of the invention disclosed in this specification and in the drawings can be used in any and all combinations.

[0020] By way of non-limiting example, the various features of the embodiments may be combined as set forth in the following aspects.

[0021] According to a first aspect, there is provided a method of scoring a glass sheet along a score line using a laser beam wherein for at least a portion of the score line, the glass is above room temperature prior to application of the laser beam, the method comprising:

(a) translating a laser beam along the score line; and

(b) translating a cooling area over the score line in tandem with the laser beam;

wherein heating by the laser beam contributes to the formation of a vent in the glass sheet and the power of the laser beam is selected so that:

(i) the temperature of the glass surface under the laser beam is less than or equal to the glass' strain point; and

(ii) the laser beam's power satisfies the relationship:

$$0.85(\alpha - \beta T_{prior}(x)) \leq P(x) \leq 1.10(\alpha - \beta T_{prior}(x))$$

where x represents distance along the score line, P(x) is the laser beam's power along the score line, $T_{prior}(x)$ is the temperature of the glass in degrees centigrade along the score line prior to application of the laser beam, $T_{prior}(x) > 25°C$ for at least one value of x, and α and β are positive constants.

[0022] According to a second aspect, there is provided the method of Aspect 1 wherein the laser beam's power satisfies the relationship:

$$0.90(\alpha - \beta T_{prior}(x)) \leq P(x) \leq 1.05(\alpha - \beta T_{prior}(x)).$$

[0023] According to a third aspect, there is provided the method of Aspect 1 wherein α and β are determined by measuring, at a plurality of glass temperatures, the minimum laser power that produces repeatable scoring and fitting those measured laser powers to a linear function.

[0024] According to a fourth aspect, there is provided the method of Aspect 3 wherein the plurality of glass temperatures includes room temperature and at least two temperatures above room temperature.

[0025] According to a fifth aspect, there is provided the method of Aspect 1 wherein $T_{prior}(x)$ is a constant.

[0026] According to a sixth aspect, there is provided the method of Aspect 1 wherein $T_{prior}(x)$ is a linear function of x.

[0027] According to a seventh aspect, there is provided the method of Aspect 1 wherein $T_{prior}(x)$ is a non-linear function of x.

[0028] According to an eighth aspect, there is provided the method of Aspect 1 wherein:

(i) $T_{prior}(x)$ is non-constant; and

(ii) the temperature of the glass surface under the laser beam is substantially constant.

[0029] According to a ninth aspect, there is provided the method of Aspect 1 wherein, for all x, $T_{prior}(x)$ satisfies the relationship:

$$T_{strain} - T_{prior}(x) \geq 100°C,$$

where T_{strain} is the strain point of the glass in degrees centigrade.

[0030] According to a tenth aspect, there is provided the method of Aspect 1 wherein, for all x, the temperature of the glass surface under the laser beam $T_{beam}(x)$ satisfies the relationship:

$$T_{beam}(x) - T_{prior}(x) \geq 80°C,$$

where $T_{beam}(x)$ is in degrees centigrade.

[0031] According to an eleventh aspect, there is provided the method of Aspect 1 wherein:

(i) the score line is divided into a plurality of segments;

(ii) an average temperature value is assigned to each segment; and

(iii) P(x) is targeted to be constant over each segment.

[0032] According to a twelfth aspect, there is provided the method of Aspect 1 wherein:

(i) $T_{prior}(x)$ is monitored over time for at least one value of x; and

(ii) the value of P(x) for at least one value of x is controlled based on the monitored value of $T_{prior}(x)$.

[0033] According to a thirteenth aspect, there is provided an apparatus for scoring a glass sheet along a score line comprising:

(a) a laser which produces a laser beam;

(b) a detector which detects the temperature of the surface of the glass sheet at at least one location; and

(c) a controller operatively connected to the laser and the detector, the controller adjusting the power P of the laser beam based on the temperature of the surface of the glass sheet detected by the detector at the at least one location.

[0034] According to a fourteenth aspect, there is provided the apparatus of Aspect 13 wherein the controller adjusts the laser beam's power so that it satisfies the relationship:

$$0.85(\alpha - \beta T_{prior}) \leq P \leq 1.10(\alpha - \beta T_{prior})$$

where T_{prior} is the temperature of the glass in degrees centigrade detected by the detector at the at least one location and α and β are positive constants.

[0035] According to a fifteenth aspect, there is provided the apparatus of Aspect 14 wherein α and β are determined by measuring, at a plurality of glass temperatures, the minimum laser power that produces repeatable scoring and fitting those measured laser powers to a linear function.

[0036] According to a sixteenth aspect, there is provided the apparatus of Aspect 15 wherein the plurality of glass temperatures includes room temperature and at least two temperatures above room temperature.

[0037] According to a seventeenth aspect, there is provided the apparatus of Aspect 13 wherein:

(i) the controller divides the score line into a plurality of segments,

(ii) the detector detects at least one temperature for each segment; and

(iii) the controller adjusts the target power of the laser beam for each segment based on the at least one temperature for the segment detected by the detector, the target laser beam power being constant over the segment.

[0038] According to an eighteenth aspect, there is provided the apparatus of Aspect 17 wherein the segments are of equal length.

[0039] According to a nineteenth aspect, there is provided an apparatus for scoring a glass sheet along a score line comprising:

(a) a laser which produces a laser beam; and

(b) a controller operatively connected to the laser;

wherein:

(i) the controller divides the score line into a plurality of segments, and

(ii) the controller adjusts the target power of the laser beam so that the target power is constant for each segment.

[0040] According to a twentieth aspect, there is provided the apparatus of Aspect 19 wherein the segments are of equal length.

[0041] According to a twenty first aspect, there is provided a method of producing a glass sheet, including producing a glass ribbon, and scoring the glass ribbon according to the method of Aspect 1.

BRIEF DESCRIPTION OF THE DRAWINGS

[0042] FIG. 1 is a plot of average laser beam power (vertical axis; watts) versus T_{prior} values (horizontal axis; °C). The square data points are off-line experimental values and the circular data points were obtained on-line using a fusion draw machine (FDM).

[0043] FIG. 2 is a plot of maximum T_{beam} values (vertical axis; °C) versus laser beam power (horizontal axis; watts). The data points are modeled values.

[0044] FIG. 3 is a plot of maximum T_{beam} values (vertical axis; °C) versus T_{prior} values (horizontal axis; °C). The data points are modeled values.

[0045] FIG. 4 is a diagram illustrating glass surface temperature during laser scoring (vertical axis; arbitrary units) versus distance along a score line (horizontal axis; arbitrary units) for a uniform background glass temperature (light shaded bars). The contribution to the glass surface temperature from the laser beam is shown by the dark shaded bars. In this figure, the laser beam contribution is constant.

[0046] FIG. 5 is a diagram illustrating glass surface temperature during laser scoring (vertical axis; arbitrary units) versus distance along a score line (horizontal axis; arbitrary units) for a gradient background glass temperature (light shaded bars). The contribution to the glass surface temperature from the laser beam is shown by the dark shaded bars. In this figure, the laser beam contribution is constant.

[0047] FIG. 6 is a diagram illustrating glass surface temperature during laser scoring (vertical axis; arbitrary units) versus distance along a score line (horizontal axis; arbitrary units) for a gradient background glass temperature (light shaded bars). The contribution to the glass surface temperature from the laser beam is shown by the dark shaded bars. In this figure, the laser beam contribution is controlled based on the local value of the background glass temperature.

[0048] FIG. 7 is a diagram illustrating glass surface temperature during laser scoring (vertical axis; arbitrary units) versus distance along a score line (horizontal axis; arbitrary units) for an arbitrary background glass temperature (light shaded bars). The contribution to the glass surface temperature from the laser beam is shown by the dark shaded bars. In this figure, the laser beam contribution is controlled based on the local value of the background glass temperature.

[0049] FIG. 8 is a schematic diagram illustrating a control system that can be used to detect glass surface temperatures and adjust laser beam power values.

[0050] FIG. 9 is a schematic diagram illustrating laser beam scoring of a glass sheet.

[0051] FIG. 10 is a schematic diagram illustrating the relationship at the glass surface between a laser beam 113 and an associated cooling area 15.

DETAILED DESCRIPTION

[0052] Based on experimental studies, it has been found that the temperature of a glass sheet affects the basic process variables of the laser scoring process, including laser beam power, quenching efficiency, and scoring speed. In addition, when glass is at an elevated temperature, its temperature distribution is generally not uniform and the distribution changes over time.

[0053] Specifically, when glass cools down, its temperature drops unevenly as a result of, among other things, environmental factors such as air flows around the glass and different glass thicknesses, e.g., in the case of a glass ribbon produced by an overflow fusion draw process, the edges of the ribbon (the beads) are thicker than the center region (quality area). The temperature gradients resulting from these non-uniform mass distributions create stress patterns in the glass, which may be a complex combination of tension areas and compression areas, which change over time and ultimately result in residual stress when the glass finally reaches room temperature.

[0054] For example, the glass ribbons produced by the overflow fusion draw process typically are formed at temperatures in the range of about 1,000°C and this temperature drops by about 700°C, e.g., to about 300°C, by the time the ribbon reaches the bottom of the draw (BOD) where scoring and the separation of individual sheets takes place. Even the removal of the bead portions from individual sheets involves above room temperature issues both in terms of the base temperature of the glass and the fact that the upper portions of the sheet are at higher temperatures than the bottom portions.

[0055] As will be recognized by skilled workers, the number of process variables which play a role in laser scoring is large thus suggesting that modifying a scoring process developed under room temperature conditions for use at elevated temperatures would be a daunting prospect. However, in accordance with the present disclosure, it has been discovered that a single primary variable, specifically, laser beam power, can be used to transition from room temperature scoring to elevated temperature scoring.

[0056] Moreover, the value of laser beam power to be used for any particular glass temperature can be readily determined from a limited number of experiments performed with laser scoring equipment and glass sheets of the type that are to be scored at the elevated temperatures. It should be noted that the equipment and glass sheets used in the experiments need not be identical to those that will be used at the elevated temperature(s), but should be representative of the elevated temperature equipment and sheets. Also, the scoring speed used in the experiments should be close to the speed (or speeds) that will be used at the elevated temperature(s), e.g., the experimental speed should be with ±20% of the speed(s) that will be used at the elevated temperature(s).

[0057] With regard to scoring speed, it should be further noted that this variable of the scoring process is typically dictated by the context in which the laser scoring is to be performed. For example, if laser scoring is to be used in connection with the separation of individual glass sheets from a ribbon, the scoring has to be performed at a rate compatible with the width of the ribbon and the desired rate of individual sheet production. For such an application, the scoring rate can, for example, be on the order of 750 millimeters/second. In terms of dealing with the challenges posed by elevated glass temperatures, scoring speed is essentially a fixed parameter and thus can only be modified slightly, if at all, in addressing those challenges.

[0058] Surprisingly, it has been discovered that modifications to laser beam power alone can be used to provide successful laser scoring of glass sheets at elevated temperatures in real time. Generally, it has been found that the coolant flow rate should be increased for elevated temperature scoring, but once this is done, the flow rate can be held constant and is not needed as a control variable. It should be noted that although in the preferred embodiments, laser beam power is used as the sole modified variable, other variables, e.g., laser beam length (e.g., "b" in FIG. 10), laser beam shape (e.g., truncated versus non-truncated), coolant flow rate, cooling area, and/or laser beam-to-cooling area spacing (e.g., "L" in FIG. 10), can be used in combination with laser beam power, if desired. Looked at another way, in addition to laser beam power, laser beam residence time, which is based on the combined effects of scoring speed, laser beam length, and laser beam shape, can be used to achieve successful scoring at elevated temperatures, but laser beam power remains the preferred modifiable variable.

[0059] In terms of real time adjustments to the laser scoring process, e.g., to accommodate glass sheet temperatures that vary over the length of the score line, laser beam power has the advantages that it can be easily varied electronically and its response time is shorter than that of other available process variables, e.g., coolant flow rate. Even with its faster response time, there will still be a limit on the achievable spatial resolution along the score line. However, in practice, it has been found that successful scoring at elevated temperatures can be achieved by dividing the score line into a plurality of segments and holding the target laser beam power constant over each segment. The segment lengths can be constant or can vary over the length of the score line, e.g., the segment lengths can be shorter where the temperature profile along the score line is changing most rapidly, e.g., in the vicinity of the beads of a glass ribbon, and longer where the temperature profile is changing more slowly, e.g., across the quality portion of a ribbon.

[0060] With the segmental approach, the response time of the laser can be readily accommodated by setting a lower limit on segment length which ensures that the laser beam power will be able to reach its target (specified) value within, for example, the first 10% of a segment. In addition to accommodating the laser's response time, the segmental approach also simplifies the circuitry for controlling the output of the laser.

[0061] In terms of adjusting laser beam power, it has been found that successful scoring of glass sheets at elevated temperatures can be achieved by adjusting the power P(x) along the length "x" of the score line based on the temperature $T_{prior}(x)$ of the glass prior to the application of the laser beam so that the power satisfies the relationship:

$$0.85(\alpha - \beta T_{prior}(x)) \leq P(x) \leq 1.10(\alpha - \beta T_{prior}(x)) \qquad \text{Eq. (1)}$$

where α and β are positive constants. In certain embodiments, the power satisfies the relationship:

$$0.90(\alpha - \beta T_{prior}(x)) \leq P(x) \leq 1.05(\alpha - \beta T_{prior}(x)) \qquad \text{Eq. (2)}$$

[0062] In addition to satisfying Eq. (1) and/or Eq. (2), the laser beam power needs to remain below the level at which the temperature of the glass surface under the laser beam would rise above the glass' strain point (e.g., 666 °C in case of Corning Incorporated's Eagle XG™ glass). In this way, overheating of the glass surface is prevented. Such overheating is undesirable because it can ablate the glass and generate high residual stress near the edge, which can entail lower edge strength, formation of edge defects, and increased edge waviness and roughness.

[0063] Preferably, α and β are pre-determined experimentally using scoring equipment, a scoring speed, and a glass corresponding to those that will be used when the actual laser scoring is performed. However, if desired, modeling can be used for this purpose either alone or in combination with an experimental study. As a further alternative, α and β can be based on prior experience with the laser scoring equipment and/or the glass being scored. It should be noted that the claims set forth below which include Eq. (1) or Eq. (2) are intended to cover laser scoring at elevated temperatures which satisfies these equations whether or not the laser power levels employed were chosen using α and β values. That is, these claims are intended to cover laser scoring at elevated temperatures which satisfy the equations whether the α and β values are determined in advance of the scoring or thereafter.

[0064] FIG. 1 illustrates the experimental approach for determining α and β values. In this figure, the horizontal axis plots T_{prior} in degrees centigrade and the vertical axis laser beam power in watts. The square data points represent the results of laboratory laser scoring experiments performed on individual glass sheets whose temperatures prior to scoring were 20, 205, 270, and 315°C. For each of these temperatures, the minimum laser power that produced repeatable scoring was experimentally determined and those powers (590, 450, 405, and 345 watts, respectively) are plotted along the vertical axis in FIG. 1. An α value of 609.4 watts and a β value of 0.8 watts/°C were then determined by fitting a straight line to this data (i.e., the dashed line in FIG. 1).

[0065] The effectiveness of Eqs. (1) and (2) in predicting the laser beam power to be employed for any particular value of T_{prior} was confirmed experimentally using a commercial scale overflow fusion draw machine (FDM). A laser scoring system was installed on the machine and used to separate individual glass sheets from a glass ribbon. The laser scoring system and the glass being scored (Corning Incorporated's 0.7 mm Eagle XG^{TM} glass) corresponded to those used for the laboratory experiments of FIG. 1. The scoring speed employed in the FDM tests (750 mm/second) was the same as that used in the laboratory experiments. At the location of the score line, the glass ribbon produced by the FDM had temperatures of between 300°C and 320°C. Using these temperatures and the above values of α and β in Eq. (1) gives:

$$314 \text{ watts} \leq P(x) \leq 406 \text{ watts for } T_{prior} = 300°\text{C}$$

and Eq. (3)

$$300 \text{ watts} \leq P(x) \leq 389 \text{ watts for } T_{prior} = 320°\text{C},$$

while Eq. (2) gives:

$$332 \text{ watts} \leq P(x) \leq 388 \text{ watts for } T_{prior} = 300°\text{C}$$

and Eq. (4)

$$318 \text{ watts} \leq P(x) \leq 371 \text{ watts for } T_{prior} = 320°\text{C}.$$

[0066] The round data points in FIG. 1 (see box 21) show representative laser beam powers that were found to produce reliable scoring at the bottom of the draw (BOD). The center of box 21 corresponds to a power of 350 watts and a temperature of 310°C. A comparison of this data with the ranges of Eqs. (3) and (4) illustrates the effectiveness of Eqs. (1) and (2) in identifying laser beam power levels for elevated values of T_{prior}.

[0067] Further experiments were performed in which laser scoring was used to trim the edges (beads) from individual glass sheets separated from the ribbon produced by the FDM. The glass temperatures for these tests were lower than those of the ribbon separation test, but still well above room temperature. For example, a typical range of temperatures during separation of individual sheets from a ribbon is 300-400°C, while for bead trimming, the individual glass sheets typically have a temperature in the 60-140°C range. Moreover, during bead trimming, the temperature along the score line typically exhibits a 50-100°C drop from the top to the bottom of the individual sheets. In addition to this temperature drop, the bead regions are also known to exhibit rather high levels of residual stress as a result of the non-uniform thickness of the glass in this region. Such high levels of residual stress further complicate the scoring process. Nevertheless, Eqs. (1) and (2) were again found to accurately predict the laser beam powers that worked reliably in the trimming procedure.

[0068] Overall, this experimental work demonstrated that in both separating individual sheets from a ribbon and in trimming beads from individual sheets, Eqs. (1) and (2) accurately bracketed the beam power levels that resulted in consistent high-speed laser scoring with high yield, good edge quality, and low residual stress.

[0069] As noted above, modeling is an alternate approach for determining α and β values. In general terms, the glass temperature (T_{beam}) under the laser beam during the laser scoring process can be defined as a sum of the background (intrinsic) glass temperature (T_{prior}) and the glass temperature change induced by exposure to the laser beam (ΔT_{laser}):

$$T_{beam} = T_{prior} + \Delta T_{laser}.$$

[0070] T_{prior} depends on the temperature of the glass environment, the sheet forming temperature, the time after sheet forming, the cooling rate and its efficiency, the uniformity of the glass cooling, and the sheet thickness, while ΔT_{laser} depends on laser beam power density, beam mode profile, beam residence time (i.e., the combination of beam size and scoring speed), and also the internal glass properties, including optical absorption at the laser wavelength and reflectivity of the glass surface. To achieve scoring, the laser beam needs to raise T_{beam} to a value (T_{beam} minimum) that will produce sufficient stress in the glass to maintain propagation of the initial flaw to form the vent, where the stress is the result of the heating produced by the beam and the subsequent quenching. The minimum stress level depends on quenching efficiency and the glass' properties, namely, its coefficient of thermal expansion and modulus of elasticity at high temperatures. The interaction between the glass and the laser beam/coolant combination also depends on the glass' thermal conductivity and its heat capacity. In addition to being above T_{beam} minimum, T_{beam} also needs to be kept below the strain point of the glass to avoid the various adverse effects discussed above that result from overheating.

[0071] FIG. 2 shows the results of modeling these various factors to predict maximum T_{beam} values (vertical axis; °C) as a function of laser beam power (horizontal axis; watts). FIG. 3 shows the modeled data replotted as maximum T_{beam} values (vertical axis; °C) versus T_{prior} values (horizontal axis; °C). In FIG. 2, the circle, "x", triangle, square, and diamond data points are for T_{prior} values of 650, 550, 450, 350, and 250 °C, respectively, while in FIG. 3, the square, diamond, triangle, circle, and asterisk data points are for laser beam powers of

400, 300, 200, 100, and 0 watts, respectively. In addition, in FIG. 2, the horizontal dashed line 13 represents the glass' strain point (e.g., 666°C) and the vertical dashed line 19 represents a laser beam power of 340 watts, i.e., a power level approximately equal to those used in the FDM test of FIG. 1. The modeled data was obtained using the commercially available ANSYS program (ANSYS, Inc., Canonsburg, Pennsylvania), although other commercially available and/or custom software can be used as desired.

[0072] From the data of FIGS. 2 and 3 (or similar plots), operating laser beam power ranges (α and β values) can be determined. In doing so, the following guidelines can be followed:

$$T_{beam}(x) - T_{prior}(x) \geq 80°C,$$

$$T_{strain} - T_{prior}(x) \geq 100°C,$$

where the first guideline ensures that the laser beam provides sufficient energy to direct the propagation of the initial flaw to form the vent along the score line and the second guideline ensures that the first guideline can be satisfied without exceeding the strain point (T_{strain}) of the glass.

[0073] As one example of the use of modeling data to obtain α and β values, a T_{beam} minimum value can be identified based on a laboratory study conducted at room temperature using a glass sheet, scoring equipment, and a scoring speed corresponding to those that will be used at the elevated temperature(s). Using that T_{beam} minimum value and the modeling data of FIGS. 2 or 3, a series of laser beam powers can be identified for a series of T_{prior} values, e.g., laser beam powers can be determined for T_{beam} values half way between T_{beam} minimum and T_{strain}. Those laser beam power values can then be plotted against the corresponding T_{prior} values to produce plotted data (in this case modeled data) of the type shown in FIG. 1. A linear fit to that data then gives α and β values for use in Eqs. (1) and (2).

[0074] However α and β are determined, the elevated temperature scoring of which they are a part can be viewed as falling into one of two major categories. The first category is scoring of glass with a high, but uniform, temperature across the sheet with just small temperature variations. This is typically the case in scoring a glass ribbon on relatively small width draw, e.g., one that produces up to Gen 5 or 6 glass sheets. The second category includes scoring of glass with significant temperature gradients, which can take place either at lower temperatures, e.g., during bead removal, or at high temperatures on large width draws or specialty draws which have a non-uniform glass temperature across the score line.

The two categories generally involve different approaches to the set-up of the laser scoring process.

[0075] Thus, if the background glass temperature variation is relatively small, then the scoring process can be run at a constant laser beam power. However, the power has to be chosen so that it is high enough to heat up the colder portions of the glass to a point where sufficient stress is created in the glass by the coolant to propagate the initial flaw to form the vent. On the other hand, the power should not be so high that the hotter portions of the glass are overheated and thus exceed the glass' strain temperature. The constant laser beam power approach works well for the majority of applications with glass temperatures of up to 400-500°C and temperature gradients not exceeding 100°C. These particular temperature values are, of course, exemplary since different values may apply depending on glass properties and the specific scoring conditions.

[0076] FIGS. 4 and 5 illustrate two examples of the constant laser beam power category. In FIG. 4, the background glass temperature (T_{prior}) is constant, while in FIG. 5, it is slowly rising across the width of the sheet (horizontal axis). In both figures, the minimum glass temperature under the laser beam (T_{beam} minimum) for reliable scoring is shown by line 11 and the strain point of the glass is shown by line 13. As can be seen, for both cases, a constant laser beam power, represented by the dark portion of the vertical bars, achieves a maximum glass temperature under the laser (vertical axis) which falls between lines 11 and 13 and is thus suitable for scoring.

[0077] If the background glass temperature gradient is too large (e.g., if it is above 100°C), then a constant laser beam power becomes unsuitable and flexible laser power adjustment is important to mitigate variations in T_{prior}. Flexible laser power can be implemented in various ways, one of which is illustrated in FIG. 8. In this figure, laser 37 produces laser light 121 which impinges upon and scores glass ribbon 27 along score line 31 thus allowing individual glass sheets 45 to be separated from the ribbon. For purposes of illustration, an overflow fusion draw process is shown in FIG. 8, it being understood that the glass ribbon (glass sheet) that is to be laser scored can be produced by any glass forming process. As illustrated in FIG. 8, the overflow fusion draw process employs a forming structure (isopipe) 25 which receives molten glass in a trough 23. The molten glass flows out and over the top of the trough and down the sides of the isopipe to form ribbon 27 at the isopipe's root 43. Pulling rollers 29 draw the ribbon away from the root at a set rate, thus determining the thickness of the ribbon.

[0078] As schematically illustrated by line 41 in FIG. 8, laser 37 is operatively connected to controller 35, e.g., a microprocessor, which controls the power level of the laser beam. As illustrated by line 39 in FIG. 8, controller 35 is also operatively connected to detector 33, e.g., an IR camera, which provides information to the controller regarding the temperature at one or more locations along score line 31. If information regarding the temperature distribution along the entire score line is desired, the detector can be scanned across the width of the ribbon or the detector can be designed to simultaneously detect temperatures from a plurality of locations along the ribbon's width.

[0079] As discussed above, flexible laser power control can be implemented using a plurality of segments which divide the width of the glass sample or, in other words, the scoring distance, into multiple segments (1, 2, ...N). In this case, controller 35 will link the position of the laser beam within each segment with a command voltage responsible for the laser discharge current. The number of segments N and their length ΔL (or, equivalently, their duration in the time domain) are then variables that are selected based on the speed of the laser response to a change in the command signal and the temperature variations exhibited by the glass temperature profile.

[0080] In cases of a constant glass temperature or a glass with small temperature gradients, where flexible power control is not required, e.g., the cases of FIGS. 4 and 5, the controller simply provides normal laser operation with the power constant and equal in all segments. (For purposes of illustration, in FIGS. 4 and 5, as well as in FIGS. 6 and 7 discussed below, the width of the glass sheet has been assumed to have been divided into 21 segments.)

[0081] When the glass temperature profile over the sample length has a significant temperature gradient, constant laser power may not keep the glass surface temperature within the process window, i.e., between lines 11 and 13 in FIGS. 4-7, everywhere along the glass sheet. In this case, controller 35 changes the laser power based on information regarding the glass' background temperature, e.g., information from detector 33. It should be noted that information from detector 33 may not be needed in some cases because the temperature profile is known for other reasons, e.g., as a result of prior use of the equipment. In such a case, the controller can be programmed to vary the laser power to compensate for the known temperature profile without the need for real time information from the detector.

[0082] FIGS. 6 and 7 illustrate two examples of the use of a variable laser power to compensate for a large variation in the temperature profile along the score line. In FIG. 6, the glass temperature rises linearly, but at a rate sufficiently large so that if a constant laser power were used to bring the coolest parts of the profile above line 11, the hottest parts would be above line 13. In this case, the controller reduces the amount of laser beam power applied to the surface as the beam scans across the score line, thus holding the glass temperature under the laser beam between the temperatures represented by lines 11 and 13 and, as shown in this figure, substantially constant. (Note that although a substantially constant temperature is desirable for many applications, it is generally not required, provided the temperature remains between the temperatures represented by lines 11 and 13.)

[0083] FIG. 7 represents the general case where the laser scoring process is to be applied to a glass sheet with a complex background glass temperature profile. Such profiles are typical for horizontal scoring of a glass ribbon where the glass is thicker towards the sides of the ribbon (the beads) and thus the temperature is higher. For this type of profile, controller 35 provides different power levels for each segment so that the ultimate temperature profile is, for example, substantially constant across the width of the ribbon.

[0084] As can be seen from the foregoing, the methods and apparatus disclosed herein can be used to achieve non-ablating laser scoring of hot glass within broad temperature ranges with arbitrary temperature and stress gradients along the scoring direction. The methods and apparatus can achieve uniform vent creation along an intended score line and are based on heating a glass surface by a laser beam up to a temperature in a range whose lower limit is defined by the stress required to maintain propagation of the initial flaw to form the vent and whose upper limit equals or, preferably, is less than the strain point of the glass. In certain embodiments, the glass temperature under the laser beam stays within these limits regardless of the background temperature of the glass through the use of flexible laser power control which produces a laser power profile along the score line which varies inversely with the glass temperature gradient. The gradient can, for example, be detected in real time using an infrared camera. In this way, process margins can be significantly increased during the scoring of glass sheets that exhibit significant glass temperature variations.

[0085] A variety of modifications that do not depart from the scope and spirit of the invention will be evident to persons of ordinary skill in the art from the foregoing disclosure. The following claims are intended to cover the specific embodiments set forth herein as well as modifications, variations, and equivalents of those embodiments.

What is claimed is:

1. A method of scoring a glass sheet along a score line using a laser beam wherein for at least a portion of the score line, the glass is above room temperature prior to application of the laser beam, the method comprising:

(a) translating a laser beam along the score line; and

(b) translating a cooling area over the score line in tandem with the laser beam;

wherein heating by the laser beam contributes to the formation of a vent in the glass sheet and the power of the laser beam is selected so that:

(i) the temperature of the glass surface under the laser beam is less than or equal to the glass' strain point; and

(ii) the laser beam's power satisfies the relationship:

$$0.85(\alpha - \beta T_{prior}(x)) \leq P(x) \leq 1.10(\alpha - \beta T_{prior}(x))$$

where x represents distance along the score line, $P(x)$ is the laser beam's power along the score line, $T_{prior}(x)$ is the temperature of the glass in degrees centigrade along the score line prior to application of the laser beam, $T_{prior}(x) > 25°C$ for at least one value of x, and α and β are positive constants.

2. The method of Claim 1 wherein the laser beam's power satisfies the relationship:

$$0.90(\alpha - \beta T_{prior}(x)) \leq P(x) \leq 1.05(\alpha - \beta T_{prior}(x)).$$

3. The method of Claim 1 wherein α and β are determined by measuring, at a plurality of glass temperatures, the minimum laser power that produces repeatable scoring and fitting those measured laser powers to a linear function.

4. The method of Claim 3 wherein the plurality of glass temperatures includes room temperature and at least two temperatures above room temperature.

5. The method of Claim 1 wherein $T_{prior}(x)$ is a constant.

6. The method of Claim 1 wherein $T_{prior}(x)$ is a linear function of x.

7. The method of Claim 1 wherein $T_{prior}(x)$ is a non-linear function of x.

8. The method of Claim 1 wherein:

(i) $T_{prior}(x)$ is non-constant; and

(ii) the temperature of the glass surface under the laser beam is substantially constant.

9. The method of Claim 1 wherein, for all x, $T_{prior}(x)$ satisfies the relationship:

$$T_{strain} - T_{prior}(x) \geq 100°C,$$

where T_{strain} is the strain point of the glass in degrees centigrade.

10. The method of Claim 1 wherein, for all x, the temperature of the glass surface under the laser beam $T_{beam}(x)$ satisfies the relationship:

$$T_{beam}(x) - T_{prior}(x) \geq 80°C,$$

where $T_{beam}(x)$ is in degrees centigrade.

11. The method of Claim 1 wherein:

(i) the score line is divided into a plurality of segments;

(ii) an average temperature value is assigned to each segment; and

(iii) P(x) is targeted to be constant over each segment.

12. The method of Claim 1 wherein:

(i) $T_{prior}(x)$ is monitored over time for at least one value of x; and

(ii) the value of P(x) for at least one value of x is controlled based on the monitored value of $T_{prior}(x)$.

13. Apparatus for scoring a glass sheet along a score line comprising:

(a) a laser which produces a laser beam;

(b) a detector which detects the temperature of the surface of the glass sheet at at least one location; and

(c) a controller operatively connected to the laser and the detector, the controller adjusting the power P of the laser beam based on the temperature of the surface of the glass sheet detected by the detector at the at least one location.

14. The apparatus of Claim 13 wherein the controller adjusts the laser beam's power so that it satisfies the relationship:

$$0.85(\alpha - \beta T_{prior}) \leq P \leq 1.10(\alpha - \beta T_{prior})$$

where T_{prior} is the temperature of the glass in degrees centigrade detected by the detector at the at least one location and α and β are positive constants.

15. The apparatus of Claim 14 wherein α and β are determined by measuring, at a plurality of glass temperatures, the minimum laser power that produces repeatable scoring and fitting those measured laser powers to a linear function.

16. The apparatus of Claim 15 wherein the plurality of glass temperatures includes room temperature and at least two temperatures above room temperature.

17. The apparatus of Claim 13 wherein:

(i) the controller divides the score line into a plurality of segments,

(ii) the detector detects at least one temperature for each segment; and

(iii) the controller adjusts the target power of the laser beam for each segment based on the at least one temperature for the segment detected by the detector, the target laser beam power being constant over the segment.

18. The apparatus of Claim 17 wherein the segments are of equal length.

19. Apparatus for scoring a glass sheet along a score line comprising:

(a) a laser which produces a laser beam; and

(b) a controller operatively connected to the laser;

wherein:

(i) the controller divides the score line into a plurality of segments, and

(ii) the controller adjusts the target power of the laser beam so that the target power is constant for each segment.

20. The apparatus of Claim 19 wherein the segments are of equal length.

21. A method of producing a glass sheet, comprising: producing a glass ribbon, and scoring the glass ribbon according to the method of claim 1.

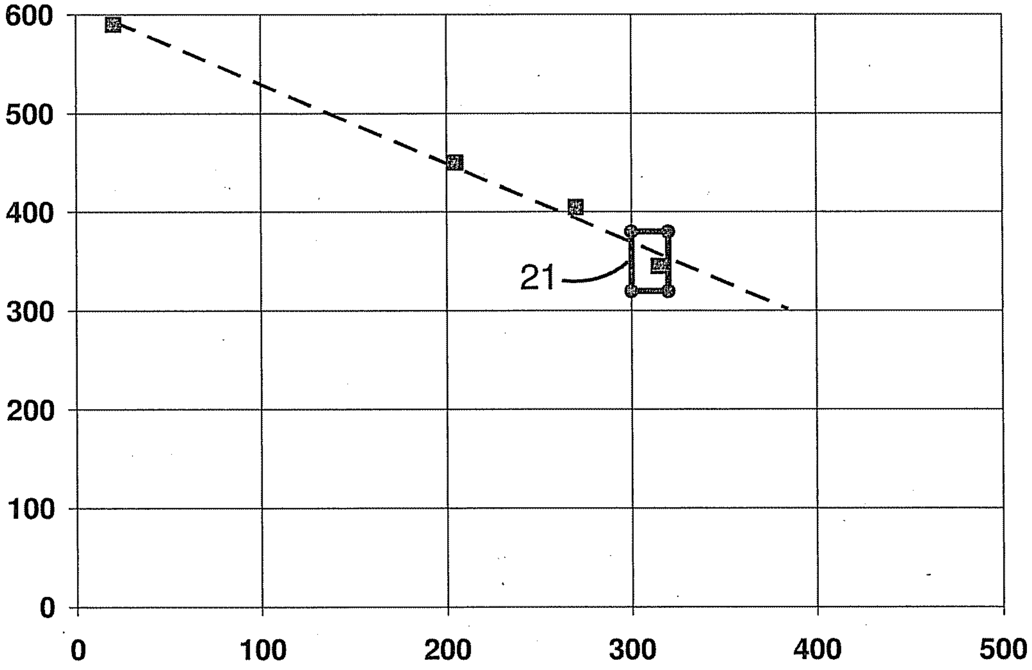

FIG. 1

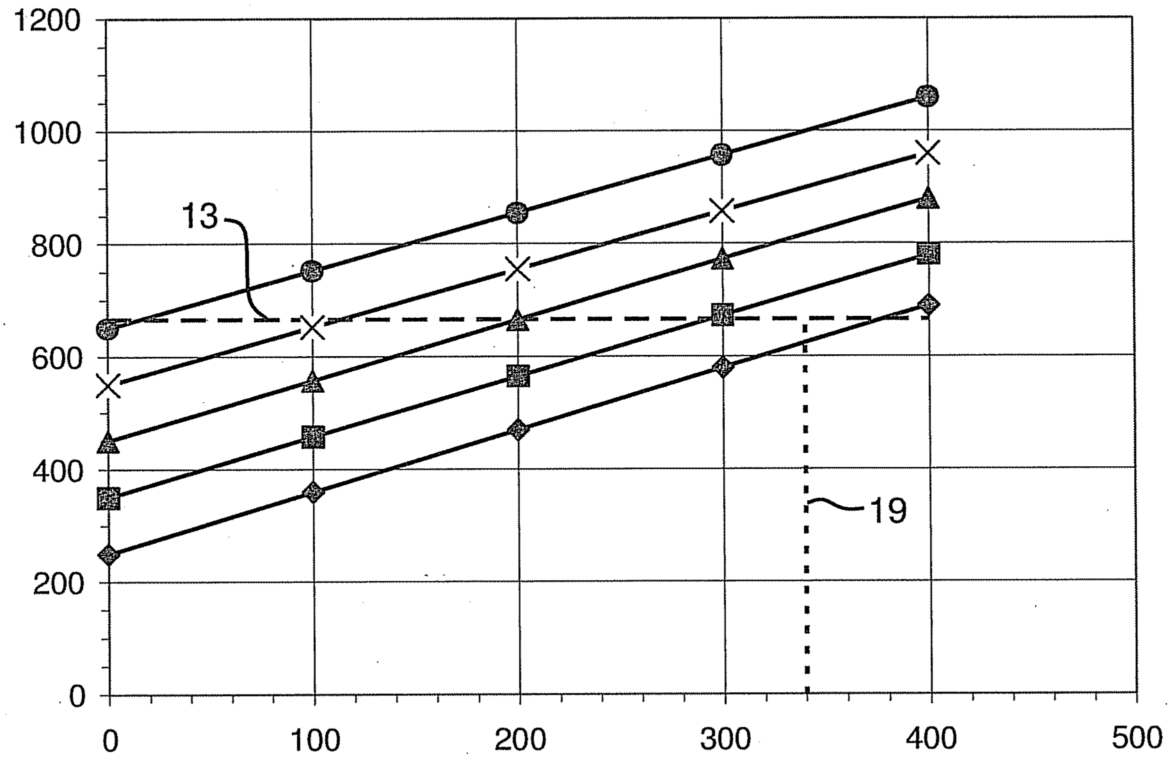

FIG. 2

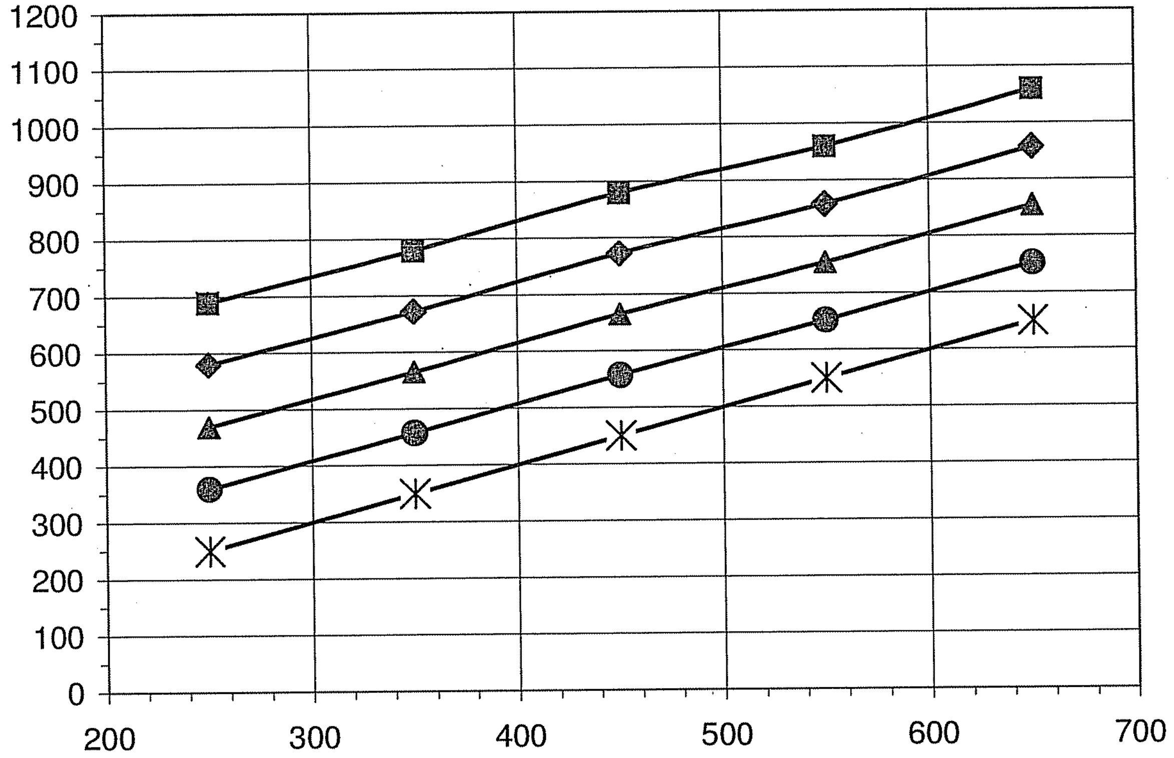
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
200
300
400
500
600
700

FIG. 3

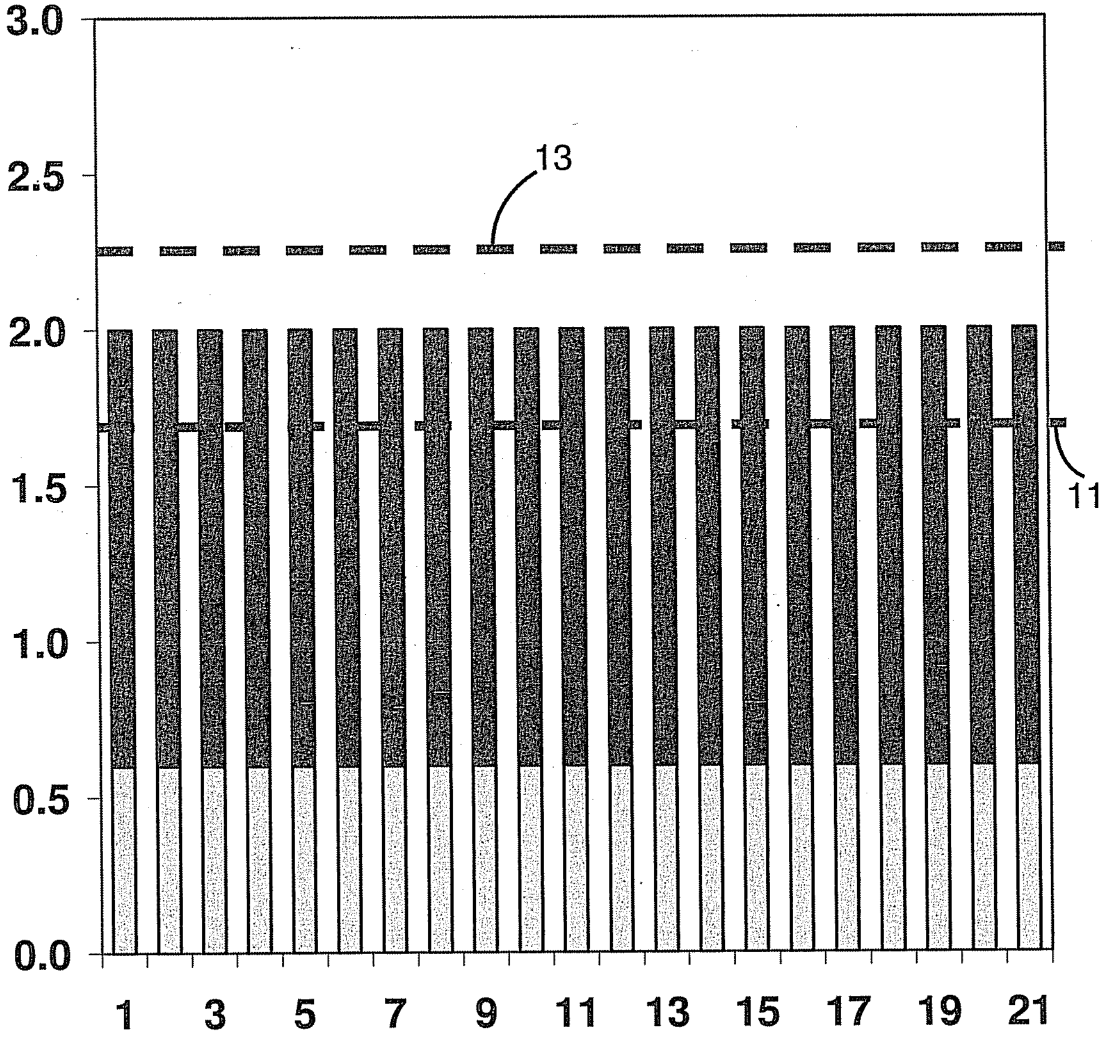

FIG. 4

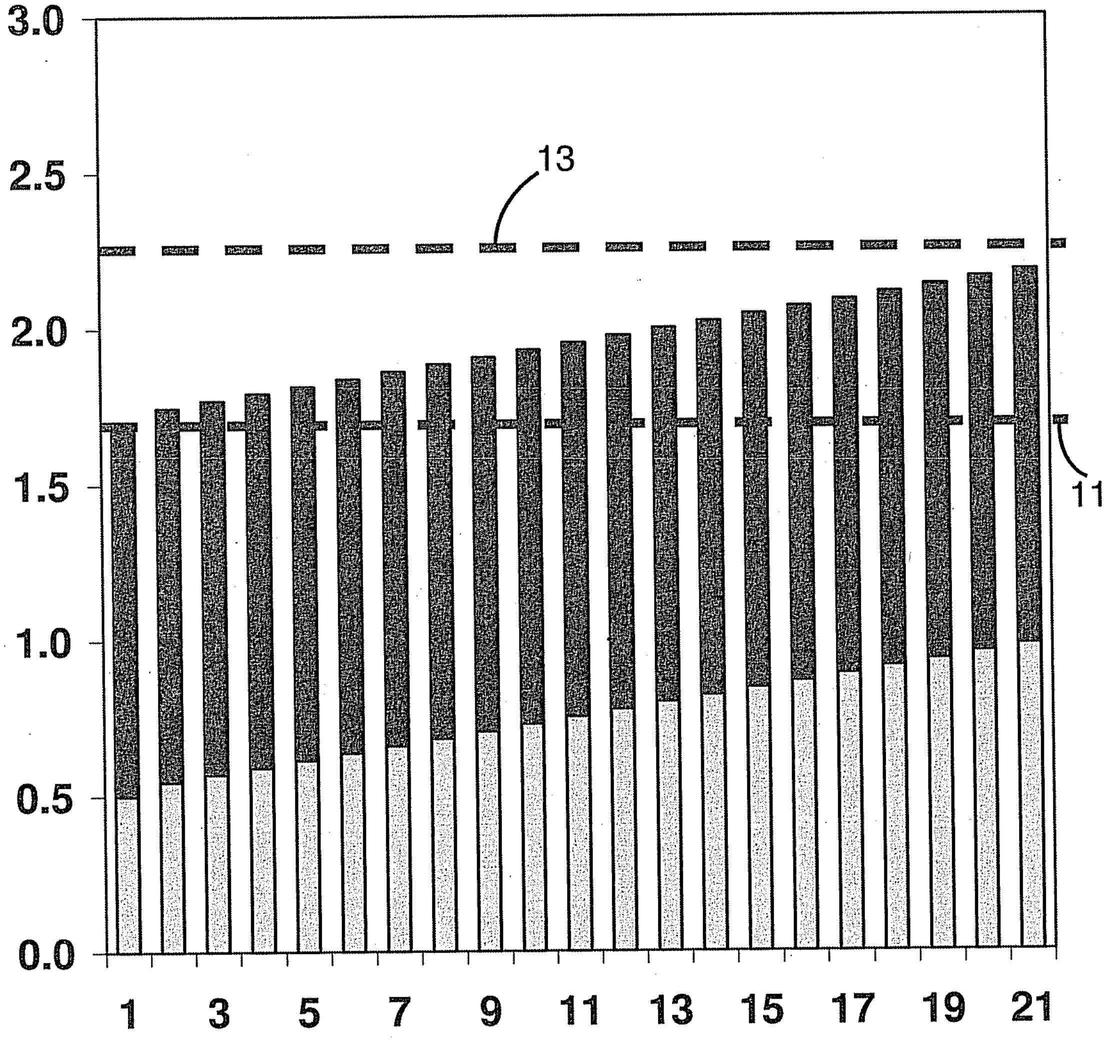

FIG. 5

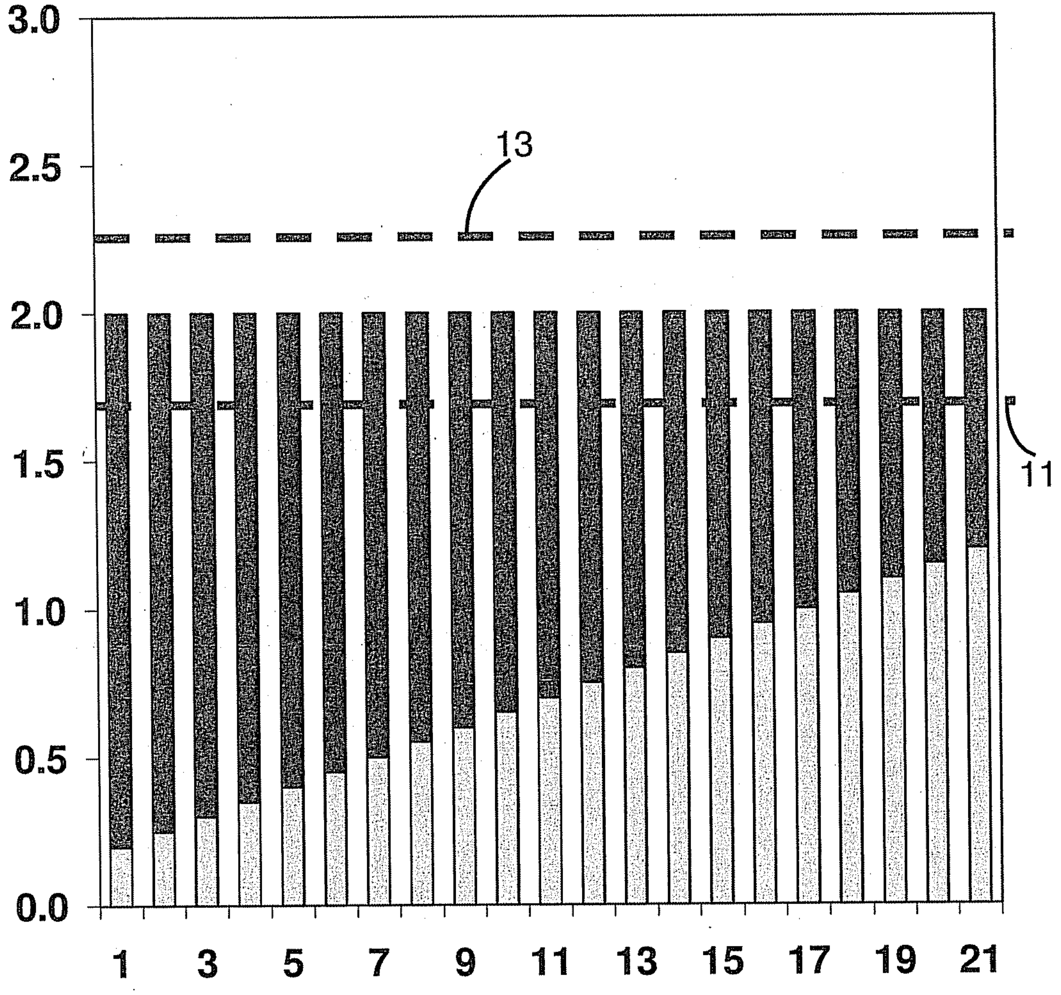

FIG. 6

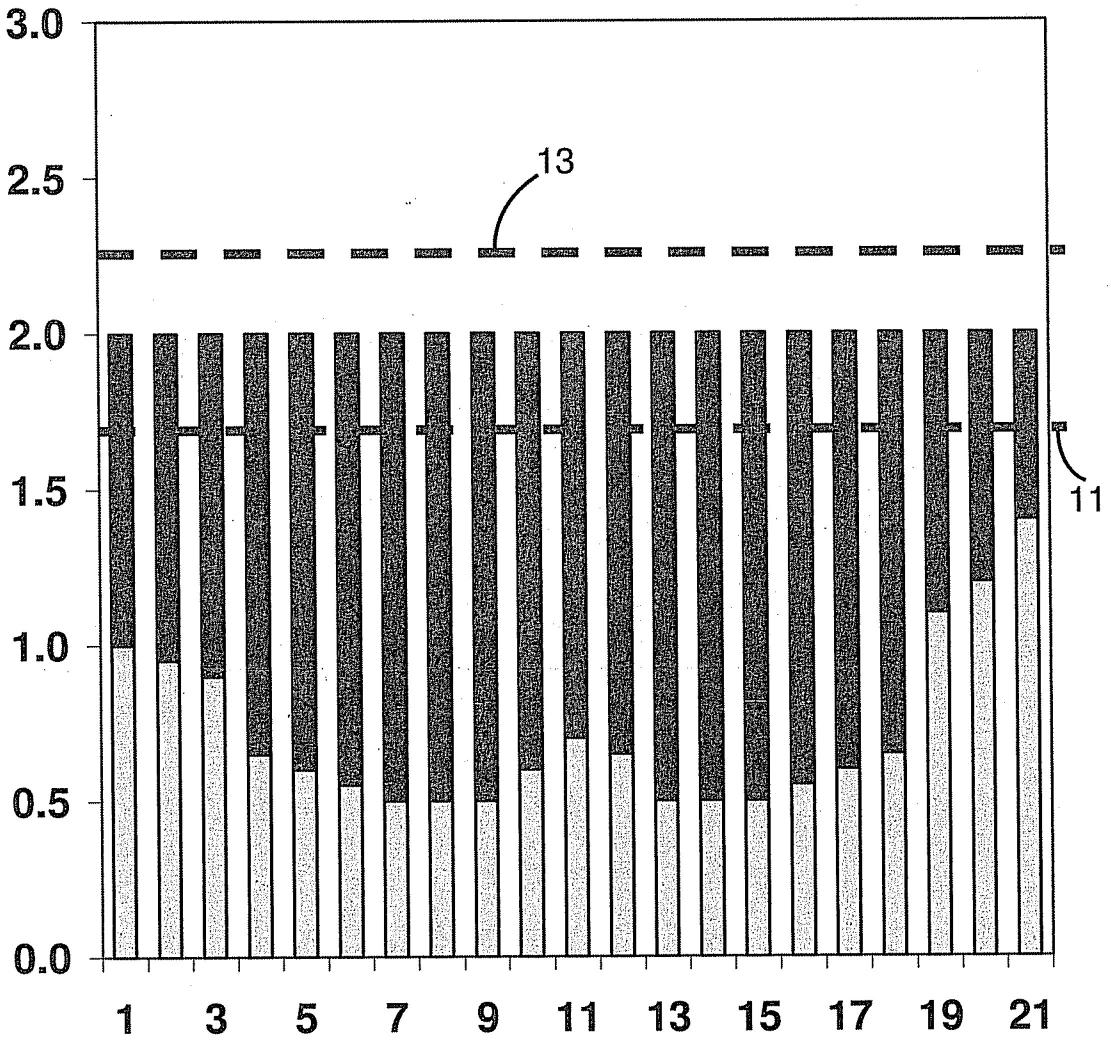

FIG. 7

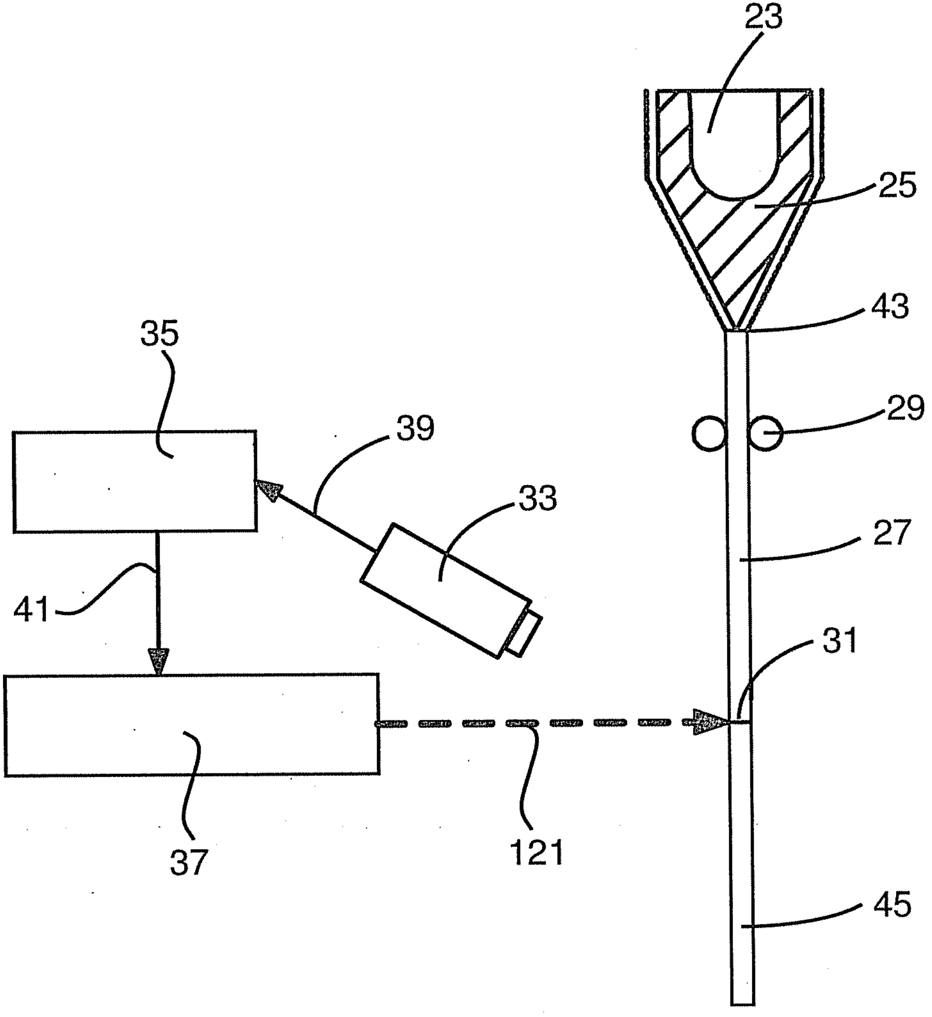

FIG. 8

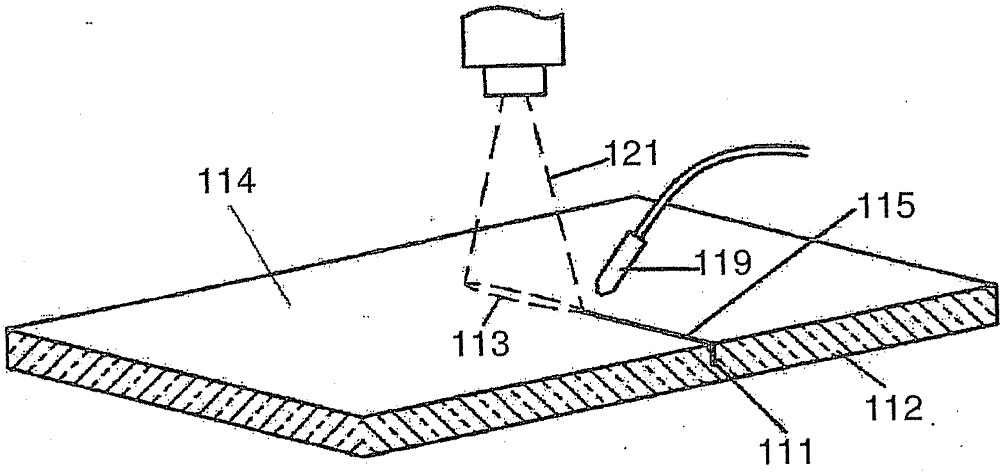

FIG. 9

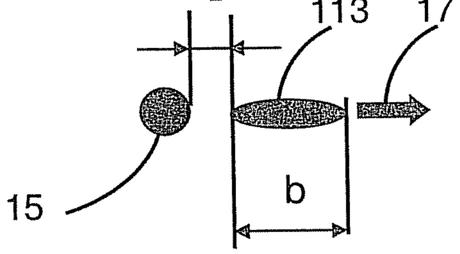

FIG. 10