(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
29 January 2015 (29.01.2015)

(10) International Publication Number
WO 2015/013092 A1

(51) International Patent Classification:
*C03B 13/16* (2006.01) *C03B 13/04* (2006.01)

(21) International Application Number:
PCT/US2014/046976

(22) International Filing Date:
17 July 2014 (17.07.2014)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/858,295 25 July 2013 (25.07.2013) US

(71) Applicant: **CORNING INCORPORATED** [US/US]; 1 Riverfront Plaza, Corning, New York 14831 (US).

(72) Inventor: **FREDHOLM, Allan Mark**; 3 Route d'Hericy, Le Clos Mallarme, F-77870 Vulaines sur Seine (FR).

(74) Agent: **BARRON, Jason A.**; Corning Incorporated, Intellectual Property Department, SP-Ti-03-01, Corning, New York 14831 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

**Published**:
— *with international search report (Art. 21(3))*

(54) Title: METHODS AND APPARATUS FOR FORMING A GLASS RIBBON

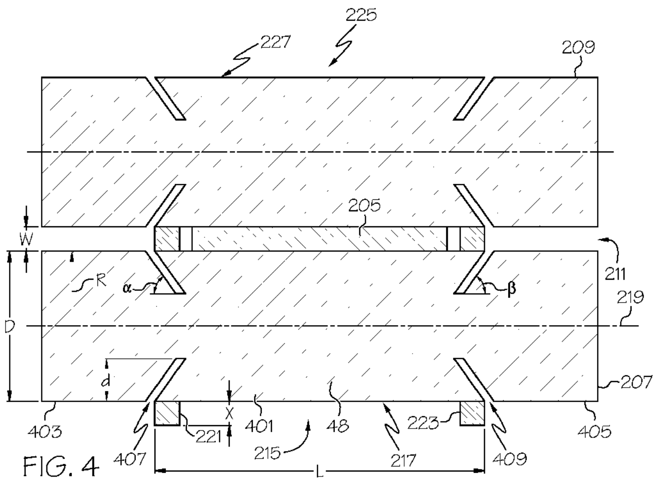


FIG. 4

(57) Abstract: A roll forming apparatus (201) includes at least one forming roll (207) being spaced from a forming body (209) to define a gap (211). The forming roll (207) includes a working zone portion(215) having a working zone surface (217) with a length extending along a rotation axis of the forming roll and a thermal resistance boundary extending at an acute angle relative to the rotation axis (219). In further examples, methods include the step of feeding a stream of molten glass through the gap to form a glass ribbon including a formed thickness. The thermal resistance boundary facilitates substantial uniform radial expansion of the working zone surface (217) relative to the rotation axis across the length of the working zone surface (217) in response to heating of the working zone portion (215) by the molten glass (205). Embodiments include a frustoconical end surface of the working zone portion (215), a plurality of bores spaced radially about the rotation axis (219) or a frustoconical groove (407, 409) defined in the forming roll (207)

WO 2015/013092 A1

# METHODS AND APPARATUS FOR FORMING A GLASS RIBBON

## CROSS REFERENCES TO RELATED APPLICATIONS

**[0001]** This application claims the benefit of priority under 35 U.S.C. § 119 to U.S. Provisional Application Serial No. 61/858295, filed on July 25, 2013, the content of which is relied upon and incorporated herein by reference in its entirety.

## TECHNICAL FIELD

**[0002]** The present disclosure relates generally to methods and apparatus for forming a glass ribbon and, more particularly, to a methods and apparatus for forming a glass ribbon with at least one forming roll and a forming body spaced to define a glass forming gap.

## BACKGROUND

**[0003]** Rolled sheet glass is typically formed using a pair of forming rolls. However, conventional glass roll forming machines that employ forming rolls typically produce glass ribbon that does not have a high precision of dimensional uniformity (e.g. thickness uniformity within +/-0.025 mm) and are unable to form thin glass ribbon below 2-3 mm in thickness. One factor that contributes to this lack of precise thickness control is the non-uniform radial thermal expansion of the forming rolls that are being heated by the stream of molten glass that is formed into the glass ribbon.

**[0004]** **FIG. 1** illustrates a schematic view of two conventional forming rolls **101**, **103** that are not necessarily drawn to scale for clarity. As show, the forming rolls are spaced from each other to define a glass forming gap **105** for receiving a stream of molten glass **107**. The forming rolls **101, 103** may expand radially in a non-uniform manner due to heating from the stream of molten glass **107** (which may be about 1000° C. or higher). For example, as indicated by dashed lines **109a, 109b**, heating of the forming rolls **101**, **103** by the stream of molten glass **107** can cause a working zone surface of each of the forming rolls to expand radially from the corresponding rotation axis in a non-uniform manner across the length of the working zone surface. The non-uniform radial expansion occurs since the central portions of the forming rolls **101**, **103** are being raised to a higher temperature than the corresponding end portions of the forming rolls **101**, **103**. Due to the non-uniform radial expansion, glass ribbon formed by the forming rolls may consequently have a relatively thin central portion when compared to the outer opposite edges of the glass ribbon.

**[0005]** There is a desire to provide forming rolls that may be used to form a glass ribbon with a thickness profile that is not substantially varied due to radial expansion of the forming rolls when heated.

## SUMMARY

**[0006]** The following presents a simplified summary of the disclosure in order to provide a basic understanding of some example aspects described in the detailed description.

**[0007]** In a first aspect, a roll forming apparatus includes a glass feed device for supplying a stream of molten glass and at least one forming roll being spaced from a forming body to define a glass forming gap between the forming roll and the forming body for receiving the stream of molten glass to form a glass ribbon having a formed thickness. The forming roll includes a working zone portion that comprises a working zone surface for engaging the stream of molten glass. The working zone surface includes a length extending along a rotation axis of the forming roll. The forming roll further includes a thermal resistance boundary extending at an acute angle relative to the rotation axis of the forming roll.

**[0008]** In one example of the first aspect, the thermal resistance boundary is configured such that the working zone surface expands radially from the rotation axis in a substantially uniform manner across the length of the working zone surface as a temperature of the working zone portion is increased from a first temperature to a second temperature.

**[0009]** In another example of the first aspect, the thermal resistance boundary comprises a frustoconical end surface of the working zone portion.

**[0010]** In yet another example of the first aspect, the thermal resistance boundary comprises a plurality of bores spaced radially about the rotation axis of the forming roll.

**[0011]** In still yet another example of the first aspect, the thermal resistance boundary comprises a frustoconical groove defined in the forming roll. For example, the frustoconical groove can be provided with one or more strength elements positioned within the groove.

**[0012]** In yet another example of the first aspect, the forming roll includes a cooling passage configured to provide fluid cooling to the forming roll.

**[0013]** In still yet another example of the first aspect, the roll forming apparatus further comprises at least one pair of gap rings, wherein the forming roll and forming body are spaced by the pair of gap rings to define the glass forming gap.

**[0014]** In another example of the first aspect, the pair of gap rings are mounted to the working zone portion of the forming roll.

**[0015]** In yet another example of the first aspect, the acute angle is from about 30° to about 60°.

**[0016]** The first aspect may be carried out alone or with one or any combination of the examples of the first aspect discussed above.

**[0017]** In a second aspect, a forming roll comprises a working zone portion comprising a working zone surface for engaging a stream of molten glass. The working zone surface includes a length extending along a rotation axis of the forming roll. The forming roll further includes a frustoconical groove defined in the forming roll and extending at an acute angle relative to the rotation axis of the forming roll.

**[0018]** In one example of the second aspect, the frustoconical groove is configured such that the working zone surface expands radially from the rotation axis in a substantially uniform manner across the length of the working zone surface as a temperature of the working zone portion is increased from a first temperature to a second temperature.

**[0019]** In another example of the second aspect, the forming roll further comprises a cooling passage configured to provide fluid cooling to the forming roll.

**[0020]** In still another example of the second aspect, the forming roll further comprises at least one gap ring mounted to the working zone portion.

**[0021]** In yet another example of the second aspect, the acute angle is from about 30° to about 60°.

**[0022]** In another example of the second aspect, the frustoconical groove extends a depth into the working zone surface that is within a range of from about 50% to about 85% of a radius of the forming roll.

**[0023]** The second aspect may be carried out alone or with one or any combination of the examples of the second aspect discussed above.

**[0024]** In a third aspect, a method is provided for forming a glass ribbon with at least one forming roll and a forming body spaced to define a glass forming gap between the forming roll and forming body. The forming roll includes a working zone portion comprising a working zone surface having a length extending along a rotation axis of the forming roll. The forming roll further includes a thermal resistance boundary extending at an acute angle relative to the rotation axis of the forming roll. The method comprises the steps of (I) supplying a stream of molten glass and (II) feeding the stream of molten glass through the gap to form a glass ribbon including a formed thickness. The thermal resistance boundary facilitates substantial uniform radial expansion of the working zone surface relative to the rotation axis across the length of the working zone surface in response to heating of the working zone portion by the molten glass.

**[0025]** In one example of the third aspect, the thermal resistance boundary of step (II) is provided as a frustoconical end surface of the working zone portion.

**[0026]** In another example of the third aspect, the thermal resistance boundary of step (II) is provided as a plurality of bores spaced radially about the rotation axis of the forming roll.

**[0027]** In yet another example of the third aspect, the thermal resistance boundary of step (II) is provided as a frustoconical groove defined in the forming roll. For example, the method can include the first step of strengthening the frustoconical groove with a plurality of strength elements positioned within the groove.

**[0028]** In another example of the third aspect, the method further comprises the step of cooling the forming roll with a fluid. For example, the step of cooling can include flowing the fluid through a cooling passage extending along the rotation axis of the forming roll. In another example, the step of cooling can include flowing the fluid against an internal central portion of the forming roll to facilitate substantial uniform expansion of the working zone surface across the length of the working zone surface in response to heating of the working zone portion by the molten glass.

**[0029]** In another example of the third aspect, the step of directing heat to outer peripheral edges of the working zone portion to facilitate substantial uniform expansion of the working zone surface across the length of the working zone surface in response to heating of the working zone portion by the molten glass.

**[0030]** In yet another example of the third aspect, the acute angle is from about 30° to about 60°.

**[0031]** The third aspect may be carried out alone or with one or any combination of the examples of the third aspect discussed above.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0032]** These and other aspects are better understood when the following detailed description is read with reference to the accompanying drawings, in which:

**[0033]** **FIG. 1** is a schematic representation depicting the expansion of two conventional forming rolls;

**[0034]** **FIG. 2** is a perspective view of an example roll forming apparatus comprising a forming roll spaced from a forming body;

**[0035]** **FIG. 3** is an end view of the example roll forming apparatus of **FIG. 2**;

**[0036]** **FIG. 4** is a cross-sectional view of the example roll forming apparatus taken along line 4-4 in **FIG. 2**;

**[0037]** **FIG. 5** is a perspective view of another example forming roll;

**[0038]** **FIG. 6** is a cross-sectional view taken along line 6-6 of **FIG. 5**;

**[0039]** **FIG. 7** is a side-view of yet another example forming roll;

**[0040]** **FIG. 8** is a cross-sectional view along frustoconical planes 8-8 of **FIG. 7**;

**[0041]** **FIG. 9** is a perspective view still another example forming roll; and

**[0042]** **FIG. 10** is a cross-sectional view along line 10-10 of **FIG. 9** showing the forming roll in use.

## DETAILED DESCRIPTION

**[0043]** Examples will now be described more fully hereinafter with reference to the accompanying drawings in which example embodiments are shown. Whenever possible, the same reference numerals are used throughout the drawings to refer to the same or like parts. However, aspects may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

**[0044]** Roll forming apparatus of the disclosure can be useful to produce glass ribbon that may be subsequently separated into glass sheets for various applications. For example, the glass sheets can be used to manufacture liquid crystal displays (LCDs), electrophoretic displays (EPD), organic light emitting diode displays (OLEDs), plasma display panels (PDPs) or other devices.

**[0045]** Turning to **FIGS. 2-4**, one example roll forming apparatus **201** can comprise a glass feed device **203** for supplying a stream of molten glass **205**. As shown in **FIG. 2**, the glass feed device **203** can comprise a fish tail slot feed although other glass feed devices may be provided in further examples. For instance, the glass feed device can comprise a fusion down draw apparatus, a fusion up draw apparatus, a redraw apparatus or other glass feed devices that may supply a stream of molten glass **205**.

**[0046]** As shown, the roll forming apparatus **201** comprises at least one forming roll **207** spaced from a forming body **209**. The forming roll and forming body can comprise various alternative refractory materials (e.g., ceramic, platinum, etc.). The materials used to manufacture the forming roll and forming body are capable of forming molten glass into a glass ribbon while maintaining the structural integrity of the forming roll and forming body. Moreover, as the forming roll and forming body will be contacting the major surfaces of the formed glass ribbon, the forming roll and forming body should be made from a material that will not damage or otherwise contaminate the major surfaces of the formed glass ribbon. For instance, the forming body can be made from various metallic alloys (e.g., stainless steel, nickel alloys).

**[0047]** The forming roll **207** and forming body **209** can define a glass forming gap **211** between the forming roll **207** and the forming body **209** for receiving the stream of molten glass **205**. As shown in **FIGS. 2-4**, the forming body **209** can comprise a forming roll that may be identical or different than the forming roll **207**. Although not shown, further examples may provide the forming body **209** as another member that is not identical or similar to the forming roll **207**. For example, the forming body **209** may comprise a member (rotatable or nonrotatable) that may cooperate with the forming roll **207** to define the glass forming gap **211**. A glass ribbon **213** can be formed as the stream of molten glass **205** passes through the forming gap **211** between the forming roll **207** and forming body **209**. The glass ribbon **213** can be formed with a thickness **T** (see **FIG. 3**) that corresponds to a width **W** (see **FIG. 4**) of the glass forming gap **211**.

**[0048]** As shown in **FIGS. 2 and 4**, the forming roll **207** includes a working zone portion **215** that comprises a working zone surface **217** for engaging the stream of molten glass **205**. The working zone surface **217** may be circular cylindrical although the working zone surface may comprise a polygonal cylindrical configuration or other shaped surface in further examples. Moreover, as shown, the working zone surface **217** has a length **L** extending along a rotation axis **219** of the forming roll **207**. The forming rolls of the disclosure further include at least one thermal resistance boundary extending at an acute angle relative to the rotation axis of the forming roll. For example, as shown in the figures, the at least one thermal resistance boundary can comprise a first thermal resistance boundary extending at an acute angle **α** relative to the rotation axis of the forming roll and a second thermal resistance boundary extending an another acute angle **β** relative to the rotation axis of the forming roll. As shown, the acute angles **α, β** may be identical to one another and facing opposite directions in some examples although the acute angles may be different in further examples. The acute angles **α, β** may have an absolute value within a range of from about 30° to about 60° although other acute angles may be provided in further examples. Providing acute angles **α, β** that are opposite to one another can help generate a circumferential dovetail portion with a trapezoidal cross-sectional portion **401** shown in **FIG. 4**.

**[0049]** As shown in **FIG. 4**, the first and second thermal resistance boundaries may be provided at respective end portions **403, 405** of the forming roll to allow heat to be more effectively retained within the working zone portion **215**. Indeed, the thermal resistance boundary provides a location of relatively higher thermal resistance to heat transfer from the working zone portion, thereby helping inhibit heat transfer out of the working zone portion **215** and into the end portions **403, 405** of the forming roll **207**. Meanwhile, the angles **α, β** of the thermal resistance boundaries can provide desirable thermal distribution characteristics of the working zone portion **215**. Indeed, by providing the thermal resistance boundary at opposite acute angles **α, β** relative to the rotation axis of the forming roll **207**, the illustrated circumferential dovetail portion with a trapezoidal cross-sectional portion **401** may be provided such that heat from the stream of molten glass **205** is retained and appropriately distributed throughout the working zone portion **215**. The resulting heat distribution in the working zone portion **215** provides a desirable temperature distribution profile that results in substantial uniform radial expansion of the working zone surface **217** relative to the rotation axis **219** across the length **L** of the working zone surface **217** in response to heating of the working zone portion **215** by the molten glass **205** from a first temperature to a second temperature. Due to the substantial uniform radial expansion of the working zone surface **217** during heating, the working zone surface **217** can maintain a substantially uniform radius across the length **L** of the working zone surface **217** throughout heating and cooling cycles of the forming roll **207**.

**[0050]** The thermal resistance boundary may comprise a wide range of alternative configurations. For example, **FIG. 4** illustrates a first thermal resistance boundary comprising a first frustoconical groove **407** and a second thermal resistance boundary comprising a second frustoconical groove **409**. Each frustoconical groove **407, 409** can be defined in the forming roll **207** to extend at the respective acute angles **α, β** relative to the rotation axis **219** of the forming roll **207**. The frustoconical grooves **407, 409** can extend completely, partially, or intermittently around the circumference of the forming roll **207**. For example, as shown, the frustoconical grooves **407, 409** each extend continuously and completely about the periphery of the forming roll **207**. Providing one or both of the frustoconical grooves as a continuous frustoconical groove that extends completely about the periphery of the forming roll can provide a more efficient boundary to thermal conduction outside the working zone portion. One or both of the frustoconical grooves may alternatively comprise discontinuities, such as aligned groove segments that are spaced apart about the periphery of the forming roll **207**. While the discontinuities may provide points of reduced thermal resistance, the discontinuities may provide structural integrity to the forming roll that may not otherwise be achieved by a continuous frustoconical groove.

**[0051]** As further illustrated in **FIG. 4**, the frustoconical grooves **407, 409** can extend a depth "**d**" into the working zone surface **217**. Various depth ranges may be provided to provide a sufficient thermal resistance boundary while maintaining the structural integrity of the forming roll **207**. For example, as shown, the forming roll can include a diameter "**D**" that is twice the radius "**R**" of the forming roll **207**. The depth "**d**" of the frustoconical grooves **407, 409** can be within a range of from about 50% to about 85% of the radius "**R**" of the forming roll **207** although other depths may be provided in further examples.

**[0052]** As further shown in **FIGS. 2-4**, the roll forming apparatus **201** may also comprise a pair of gap rings **221**, **223**, wherein the forming roll **207** and the forming body **209** are spaced from each other by the pair of gap rings **221**, **223** to define the glass forming gap **211**. While the thermal resistant boundaries of the forming roll **207** and the forming body **209** are configured to maintain a substantially uniform width **W** along length **L** during radial expansion of the forming roll and forming body, the gap rings **221**, **223** may be configured to maintain a substantially constant width **W** during this radial expansion. In the example shown in **FIGS. 2-4**, the gaps rings **221**, **223** are mounted to the working zone portion **215** of the forming roll **207** and protrude from the working zone surface **217** by a distance **X**. In alternative examples, one or both of the gap rings **221, 223** may be mounted to a working portion **225** of the forming body **209** and protrude from a working zone surface **227** of the working portion **225** by a distance **X**. In further examples, as further shown by the gap rings **222, 224** in hidden lines in **FIG. 2**, both the forming roll **207** and the forming body **209** may each include a pair of gap rings that each extend from the corresponding working zone surface **217, 227** by a distance **X/2**. Respective gap rings **221, 222** and **223, 224** can engage one another in operation such that the total spacing of the working zone surfaces **217, 227** provided by the gap rings is **X**.

**[0053]** Thus, the pair of gap rings **221**, **223** can ensure that, during expansion, the working zone surfaces **217, 227** of the forming roll **207** and the forming body **209** will remain separated by a constant width **W** that corresponds to the distance **X**. Accordingly, a pair of gap rings **221**, **223** may be selected that protrude from the working zone surface **217** by a predetermined distance **X** to form a glass ribbon **213** having a substantially uniform thickness **T** that corresponds to the predetermined distance **X**. As such, thin glass ribbons with a uniform thickness of 1 mm or less can be easily formed without having to predict how the width **W** may change during the expansion of forming rolls absent the use of gap rings. Moreover, even though the gap rings **221**, **223** may themselves expand as they rise in temperature during the roll forming process, the expansion of distance **X** should be nominal when distance **X** is small (as is the case when forming thin glass sheets of 1 mm or less). Furthermore, the gap rings **221**, **223** may be coated with a low thermal conductivity ceramic coating or they may comprise a material having a low coefficient of thermal expansion to reduce the effects of heat on the expansion of distance **X**.

**[0054]** The pair of gaps rings **221**, **223** may be integral with the forming roll **207** and/or forming body **209** or they may be mounted separately to the forming roll **207**

and/or forming body **209**. Additionally, as discussed above, there may be a second pair of gap rings (not shown) mounted to the forming body **209** that contact the first pair of gap rings **221**, **223** on the forming roll **207**. Moreover, although the example provided shows a pair of gaps rings **221**, **223** mounted on the working zone portion **215** of forming roll **207**, they can alternatively be mounted to the end portions **403**, **405** of the forming roll **207**. However, since the working zone portion **215** will retain heat from the stream of molten glass **205** and therefore expand at a rate different from (and greater than) the end portions **403**, **405**, mounting the gap rings **221**, **223** on the working zone portions **215, 225** can lead to a better control of the width **W** along length **L**. In other words, mounting the gap rings **221**, **223** to the end portions **403**, **405** will ensure that the end portions **403**, **405** remain a constant distance apart but may not ensure that the working zone surfaces **217**, **227** will remain a constant distance apart since the working zone surfaces **217**, **227** may expand at a rate different from the end portions **403**, **405**.

**[0055]** As shown in **FIG. 4**, each of the forming roll **207** and the forming body **209** may have a similar (such as the illustrated identical) thermal resistance boundary configuration. In fact, as discussed above, the forming body **209** may be identical to the forming roll **207** such that the forming roll **207** and the forming body **209** form a pair of substantially identical forming rolls as shown. One or both of the forming roll and forming body may have alternative constructions for the thermal resistance boundaries. For example, one or both of the forming roll **207** and/or the forming body **209** can comprise the forming roll **501** shown in **FIGS. 5 and 6**. The forming roll **501** comprises a working zone portion **503** comprising a working zone surface **505** for engaging the stream of molten glass **205**. The working zone surface **505** including a length **L** extending along a rotation axis **507** of the forming roll **501**. As shown in **FIG. 6**, the forming roll **501** includes a first thermal resistance boundary comprising a first frustoconical end surface **601** and a second thermal resistance boundary comprising a second frustoconical end surface **603**. Each frustoconical end surface **601, 603** can extend at the respective acute angles **$\alpha$, $\beta$** relative to the rotation axis **507** of the forming roll **501**.

**[0056]** As further illustrated in **FIG. 6**, the frustoconical end surfaces **601, 603** can extend a depth "**d**" into the working zone surface **505**. Various depth ranges may be provided to provide a sufficient thermal resistance boundary while maintaining the structural integrity of the forming roll **503**. For example, as shown, the forming roll can include a diameter "**D**" that is twice the radius "**R**" of the forming roll **503**. The depth "**d**" of the frustoconical end surface **601, 603** can be within a range of from about 50% to about 85% of the radius "**R**" of the forming roll **503** although other depths may be provided in further examples.

**[0057]** As shown in **FIG. 6**, the end surface **601, 603** do not face a corresponding surface of end portions **605, 607** of the forming roll **501**. As such, the thermal resistance boundaries of **FIGS. 5 and 6** may have a higher thermal resistance to heat transfer than the thermal resistance boundaries of **FIGS. 2-4**. Although not shown, the forming roll **501** may optionally include a plurality of strengthening ribs extending radially about the rotation axis **507** and spanning between the end surfaces **601, 603** and the respective end portions **605, 607** to increase the structural strength of the forming roll **501**.

**[0058]** In further examples, one or both of the forming roll and forming body can comprise the forming roll **701** shown in **FIGS. 7 and 8**. The forming roll **701** comprises a working zone portion **703** comprising a working zone surface **705** for engaging the stream of molten glass **205**. The working zone surface **705** including a length **L** extending along a rotation axis **707** of the forming roll **701**. The forming roll **701** includes a first thermal resistance boundary comprising a first plurality of bores **709** and a second thermal resistance boundary comprising a second plurality of bores **711**. As indicated by the hidden lines **713** of each bore **715**, the bores can extend along a bore axis **801** (see **FIG. 8**) at the respective acute angles **α, β** relative to the rotation axis **707** of the forming roll **701** as indicated by frustoconical sectional planes 8-8. **FIG. 8** illustrates the array of bores **715** radially spaced about the rotation axis **707** of the forming roll **701** along corresponding frustoconical planes 8-8 of **FIG. 7**. The bores **715** may or may not be equally spaced from each other. Additionally, the bores **715** may vary in number, depth, and size from the example shown. In these alternative embodiments, as each bore axis **801** extends at the respective acute angles **α, β**, the thermal resistant boundaries similarly extend at acute angles relative to the rotation axis of the forming roll **701**. Providing the thermal resistance boundaries as respective pluralities of bores can provide enhanced structural integrity when compared to other designs that remove substantial portions of the forming roll to create the thermal resistance boundaries.

**[0059]** In still further examples, one or both of the forming roll and forming body can comprise the forming roll **901** shown in **FIGS. 9 and 10**. The forming roll **901** comprises a working zone portion **903** comprising a working zone surface **905** for engaging the stream of molten glass **205**. The working zone surface **905** including a length **L** extending along a rotation axis **907** of the forming roll **901**. The forming roll **901** includes a first thermal resistance boundary comprising a first frustoconical groove **909** and a second thermal resistance boundary comprising a second frustoconical groove **911**. Each frustoconical groove **909, 911** can be defined in the forming roll **901** to extend at the previously described respective acute angles **α, β** relative to the rotation axis **907** of the forming roll **901**. As with the frustoconical grooves **407, 409** illustrated in **FIG. 4**, the frustoconical grooves **909**, **911** can extend completely, partially, or intermittently around the circumference of the forming roll **901**. For example, as shown, the frustoconical grooves **909, 911** each extend completely about the periphery of the forming roll **901**. Providing one or both of the frustoconical grooves as a frustoconical groove that extends completely about the periphery of the forming roll **901** can provide a more efficient boundary to thermal conduction outside the working zone portion.

**[0060]** Optionally, one or both of the frustoconical grooves may alternatively comprise discontinuities to increase the structural integrity of the forming roll that may not otherwise be achieved by the continuous frustoconical groove. For example, as shown in **FIG. 10**, each of the frustoconical grooves **909, 911** may include a plurality of strength elements, such as the illustrated weld points **1001, 1003**, positioned within the groove to strengthen the forming roll **901**. The weld points **1001, 1003** attach the working zone portion **903** to end portions **913, 915** of the forming roll **901**, thus adding strength and rigidity to the forming roll **901**. The weld points **1001, 1003** can extend completely or partially around the circumference of the forming roll **901**. There can also be more than one weld point positioned within each groove. Moreover, the weld points **1001, 1003** can be positioned radially so that they are closer to the surface of the forming roll **901** or they can be positioned deeper within the grooves so that they are closer to the rotation axis of the forming roll **901**.

**[0061]** The forming rolls of the disclosure may also include an optional cooling passage. For example, as shown in **FIG. 10**, the forming roll **901** includes an optional cooling passage **1007** configured to provide fluid cooling to the forming roll **901**. In some examples, the cooling passage **1007** may be coaxial with the forming roll **901** and extends through the working zone portion **903**. As further illustrated in **FIG. 10**, the frustocontical grooves **909, 911** can extend a depth "**d**" into the working zone surface **905**. Various depth ranges may be provided to provide a sufficient thermal resistance boundary while maintaining the structural integrity of the forming roll **903**. For example, as shown, the forming roll can include a diameter "**D**" that is twice the radius "**R1**" of the forming roll **903**. Moreover, the cooling passage **1007** can include a radius "**R2**" wherein a wall thickness "**WT**" is formed between the working zone surface **905** and the interior wall surface of the cooling passage **1007**. The depth "**d**" of the frustoconical grooves **909, 911** can be within a range of from about 50% to about 85% of the wall thickness "**WT**" of the forming roll **903** although other depths may be provided in further examples.

**[0062]** Cooling fluid may be supplied to this cooling passage **1007** an dispersed as a cooling fluid stream **1009** to cool the forming roll **901** and reduce its expansion during the roll forming process. The cooling fluid may be water or compressed air or some other cooling fluid. As shown in **FIG. 10**, a conduit **1005** may be provided within the cooling passage **1007** to deliver the cooling fluid and direct the cooling fluid stream **1009** against an internal central portion of the forming roll **901**.

**[0063]** During the roll forming process, the central portion of the forming roll **901** experiences a greater amount of heat than the outer peripheral portions of the forming roll **901**. Thus, by directing the cooling fluid towards the central portion of the forming roll **901**, the temperature of the central portion can be controlled so that the central portion expands at a rate substantially uniform to outer peripheral portions of the working zone portion **903**. Accordingly, directing the fluid stream **1009** against an internal central portion of the forming roll **901** can facilitate substantial uniform expansion of the working zone surface **905** across the length **L** of the working zone surface **905** in response to heating of the working zone portion **903** by the stream of molten glass **205**.

**[0064]** In addition or in alternative to flowing a cooling fluid through a cooling passage, heat **H** may be directed to outer peripheral edges of the working zone portion **903** to facilitate substantial uniform expansion of the working zone surface **905** across the length **L** of the working zone surface **905** in response to heating of the working zone portion **903** by the molten glass, as shown in **FIG. 10**. By directing heat towards the outer peripheral edges of the working zone portion **903**, the temperature of the outer peripheral portions can be controlled so that the outer peripheral portions expand at a rate substantially uniform to the central portion of the working zone portion **903**.

**[0065]** Methods of forming the glass ribbon **213** will now be described and can apply to any of the example forming roll/forming body configurations of the disclosure. The method can be carried out with at least one forming roll and a forming body spaced to define a glass forming gap between the forming roll and forming body. As mentioned previously, the forming body can comprise various configurations and may be similar or identical to the forming roll. For example, as shown in **FIGS. 2 and 4**, both the forming roll **207** and the forming body **209** including working zone portions **215, 225** comprising the working zone surfaces **217, 227** including the length **L** extending along the rotation axis **219** of the corresponding forming roll **207** and forming body **209**. As mentioned previously, the forming roll and forming body can each include the thermal resistance boundary comprising the frustoconical grooves **407, 409** defined in the forming roll **207** that each extend at the acute angle **α, β** relative to the respective rotation axis (e.g., rotation axis **219**). The method can provide the acute angles **α, β** within a range of from about 30° to about 60° although other acute angles may be used in further examples.

**[0066]** As discussed previously, other thermal resistance boundary configurations may be used in further examples. For instance, **FIGS. 5 and 6** illustrate the thermal resistance boundary comprising the frustoconical end surface **601, 603** of the working zone portion **503**. **FIGS. 7 and 8** illustrated another example wherein the thermal resistance boundary comprises the plurality of bores **709, 711** spaced radially about the rotation axis **707** of the forming roll. As shown in **FIG. 9 and 10**, another examples provides the thermal resistance boundary as the frustoconical groove **909, 911** with the plurality of strength elements (e.g., weld points **1001, 1003**) positioned within the groove.

**[0067]** Turning to **FIGS. 2 and 3**, the methods can further include the steps of supplying the stream of molten glass **205** and feeding the stream of molten glass through the gap **211** to form the glass ribbon **213** including the formed thickness **T**. The thermal resistance boundary of each example of the disclosure facilitates substantial uniform radial expansion of the working zone surface relative to the rotation axis across the length of the working zone surface in response to heating of the working zone portion by the molten glass. In one example, the method can further include the step of cooling the forming roll with a fluid. For instance, as shown in **FIG. 10**, the method can include flowing the fluid through the cooling passage **1007** extending along the rotation axis **907** of the forming roll **901**. As further shown, the method can include the step of cooling by flowing the fluid against the internal central portion of the forming roll, for example, by way of the cooling fluid stream **1009**. Flowing the fluid against the internal central portion of the forming roll can facilitate substantial uniform expansion of the working zone surface **905** across the length **L** of the working zone surface **905** in response to heating of the working zone portion **903** by the molten glass **205**.

**[0068]** As further shown schematically by "**H**" in **FIG. 10**, the method can also include the step of heating the outer peripheral edges of the working zone portion **903** to facilitate substantial uniform expansion of the working zone surface **905** across the length **L** of the working zone surface **905** in response to heating of the working zone portion **903** by the molten glass **205**.

**[0069]** It will be apparent to those skilled in the art that various modifications and variations can be made without departing from the spirit and scope of the claimed invention.

## CLAIMS

What is claimed is:

1. A roll forming apparatus comprising:

a glass feed device for supplying a stream of molten glass; and

at least one forming roll being spaced from a forming body to define a glass forming gap between the forming roll and the forming body for receiving the stream of molten glass to form a glass ribbon including a formed thickness,

wherein the forming roll comprises a working zone portion comprising a working zone surface for engaging the stream of molten glass, the working zone surface including a length extending along a rotation axis of the forming roll, wherein the forming roll includes a thermal resistance boundary extending at an acute angle relative to the rotation axis of the forming roll.

2. The apparatus of claim 1, wherein the thermal resistance boundary is configured such that the working zone surface expands radially from the rotation axis in a substantially uniform manner across the length of the working zone surface as a temperature of the working zone portion is increased from a first temperature to a second temperature.

3. The apparatus of claim 1 or claim 2, wherein the thermal resistance boundary comprises a frustoconical end surface of the working zone portion.

4. The apparatus of any of claims 1-3, wherein the thermal resistance boundary comprises a plurality of bores spaced radially about the rotation axis of the forming roll.

5. The apparatus of any of claims 1-4, wherein the thermal resistance boundary comprises a frustoconical groove defined in the forming roll.

6. The apparatus of claim 5, wherein the frustoconical groove is provided with one or more strength elements positioned within the groove.

7. The apparatus of any of claims 1-6, wherein the forming roll includes a cooling passage configured to provide fluid cooling to the forming roll.

8. The apparatus of any of claims 1-7, further comprising at least one pair of gap rings, wherein the forming roll and forming body are spaced by the pair of gap rings to define the glass forming gap.

9. The apparatus of any of claims 1-8, wherein pair of gap rings are mounted to the working zone portion of the forming roll.

10. The apparatus of any of claims 1-9, wherein the acute angle is from about $30^{o}$ to about $60^{o}$.

11. A forming roll comprising:

a working zone portion comprising a working zone surface for engaging a stream of molten glass, the working zone surface including a length extending along a rotation axis of the forming roll; and

a frustoconical groove defined in the forming roll and extending at an acute angle relative to the rotation axis of the forming roll.

12. The forming roll of claim 11, wherein the frustoconical groove is configured such that the working zone surface expands radially from the rotation axis in a substantially uniform manner across the length of the working zone surface as a temperature of the working zone portion is increased from a first temperature to a second temperature.

13. The forming roll of claim 11 or claim 12, further comprising a cooling passage configured to provide fluid cooling to the forming roll.

14. The forming roll of any of claims 11-13, further comprising at least one gap ring mounted to the working zone portion.

15. The forming roll of any of claims 11-14, wherein the acute angle is from about 30° to about 60°.

16. The forming roll of any of claims 11-15, wherein the frustoconical groove extends a depth into the working zone surface that is within a range of from about 50% to about 85% of a radius of the forming roll.

17. A method of forming a glass ribbon with at least one forming roll and a forming body spaced to define a glass forming gap between the forming roll and forming body, wherein the forming roll comprises a working zone portion comprising a working zone surface including a length extending along a rotation axis of the forming roll, wherein the forming roll includes a thermal resistance boundary extending at an acute angle relative to the rotation axis of the forming roll, the method comprising the steps of:

(I) supplying a stream of molten glass; and

(II) feeding the stream of molten glass through the gap to form a glass ribbon including a formed thickness, wherein the thermal resistance boundary facilitates substantial uniform radial expansion of the working zone surface relative to the rotation axis across the length of the working zone surface in response to heating of the working zone portion by the molten glass.

18. The method of claim 17, wherein the thermal resistance boundary of step (II) is provided as a frustoconical end surface of the working zone portion.

19. The method of claim 17 or claim 18, wherein the thermal resistance boundary of step (II) is provided as a plurality of bores spaced radially about the rotation axis of the forming roll.

20. The method of any of claims 17-19, wherein the thermal resistance boundary of step (II) is provided as a frustoconical groove defined in the forming roll.

21. The method of claim 20, further comprising the step of strengthening the frustoconical groove with a plurality of strength elements positioned within the groove.

22. The method of any of claims 17-21, further comprising the step of cooling the forming roll with a fluid.

23. The method of any of claims 17-22, wherein the step of cooling includes flowing the fluid through a cooling passage extending along the rotation axis of the forming roll.

24. The method of claim 22, wherein the step of cooling includes flowing the fluid against an internal central portion of the forming roll to facilitate substantial uniform expansion of the working zone surface across the length of the working zone surface in response to heating of the working zone portion by the molten glass.

25. The method of any of claims 17-24, further comprising the step of directing heat to outer peripheral edges of the working zone portion to facilitate substantial uniform expansion of the working zone surface across the length of the working zone surface in response to heating of the working zone portion by the molten glass.

26. The method of any of claims 17-25, wherein the acute angle is from about 30° to about 60°.

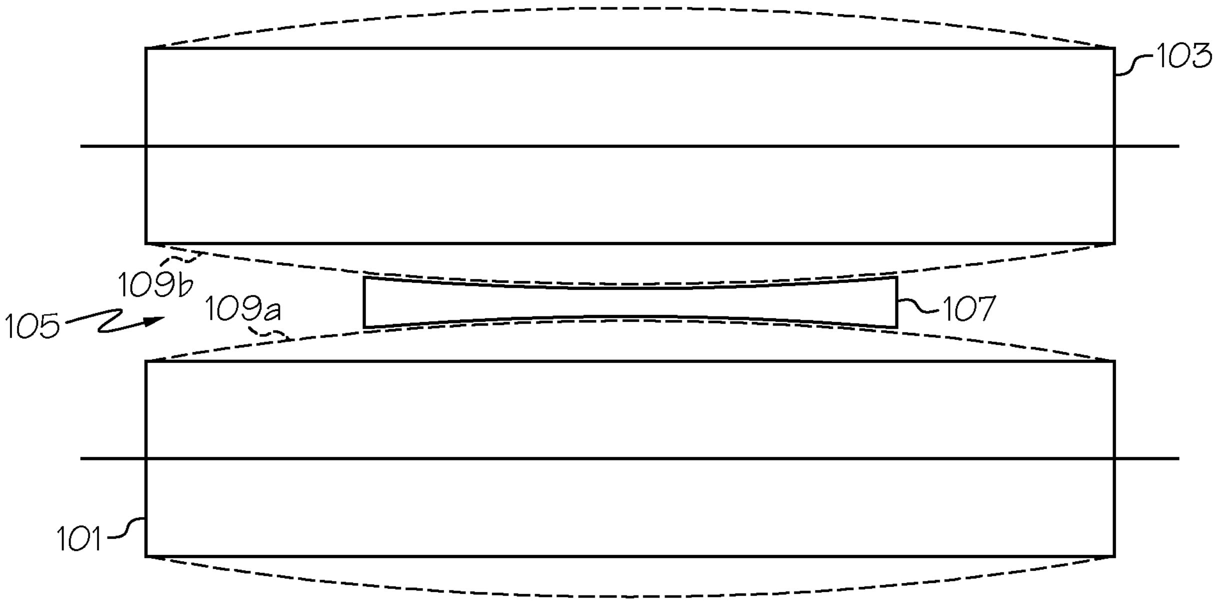


FIG. 1

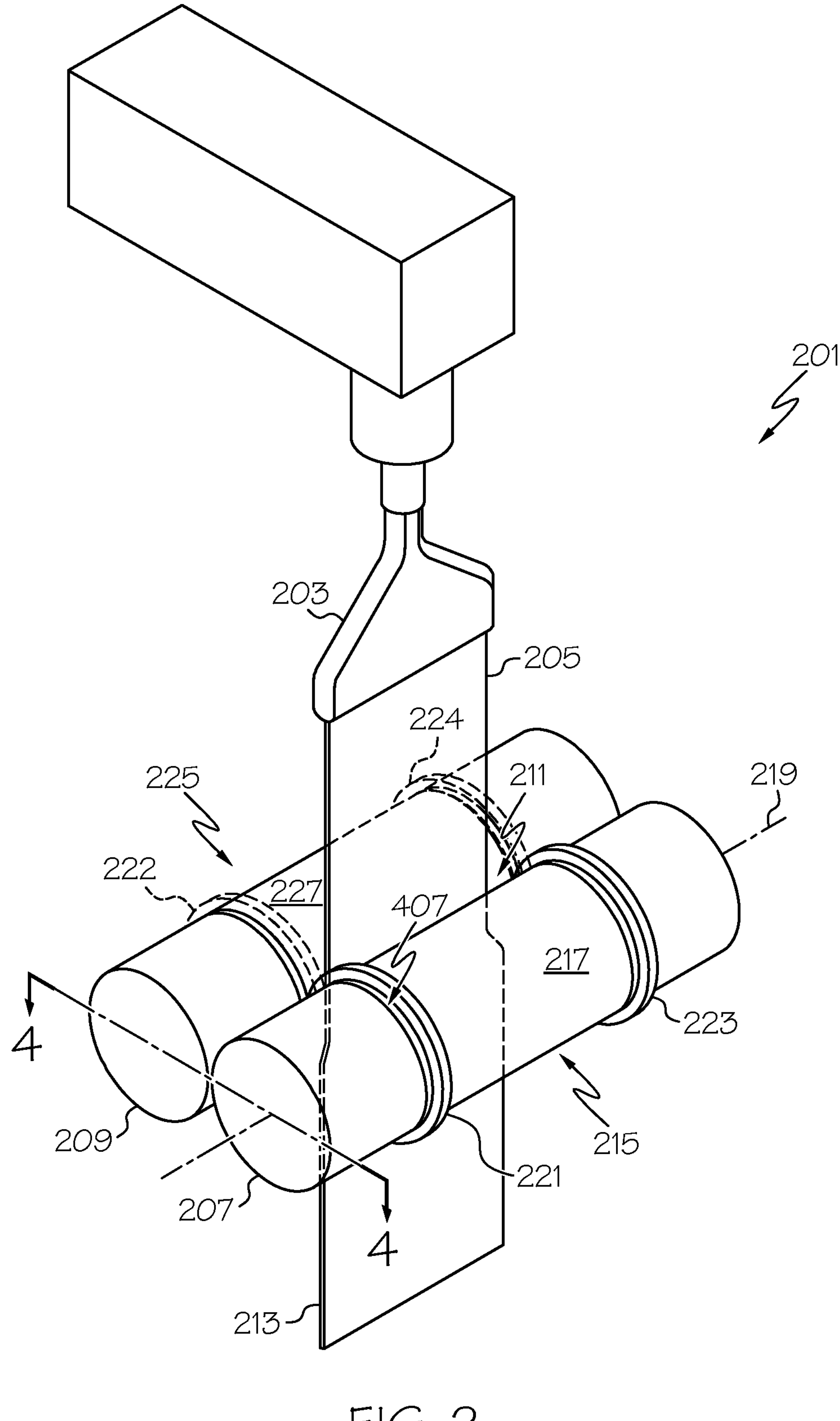
201
203
205
224
225
211
219
222
227
407
217
4
223
209
215
221
207
4
213

FIG. 2

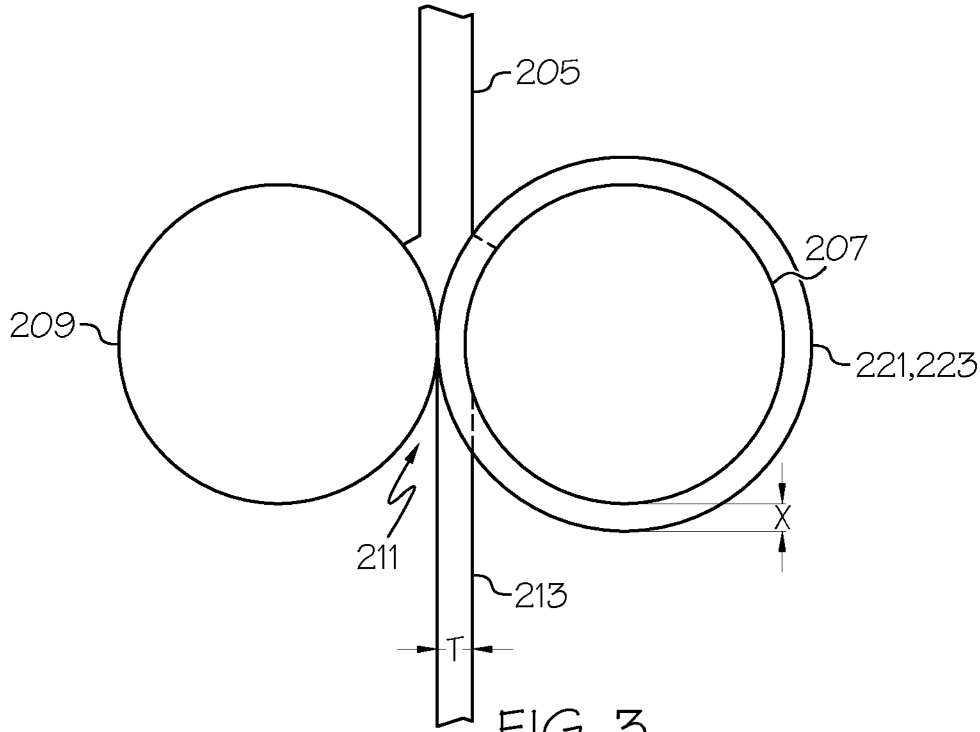
205
207
209
221,223
211
213
X
T

FIG. 3

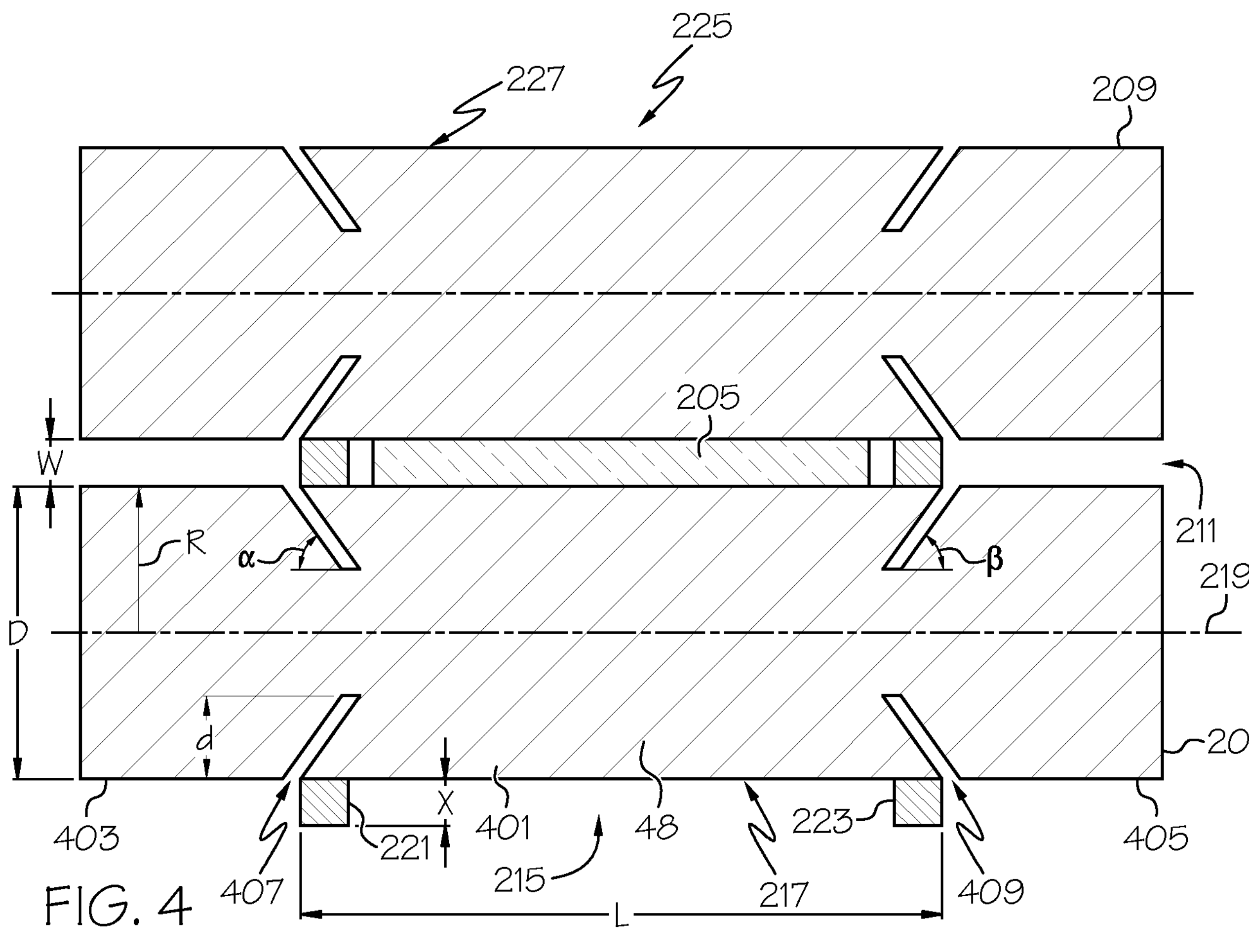
225
227
209
205
W
211
R
α
β
219
D
d
207
X
403
221
401
48
223
405
215
217
407
409
L

FIG. 4

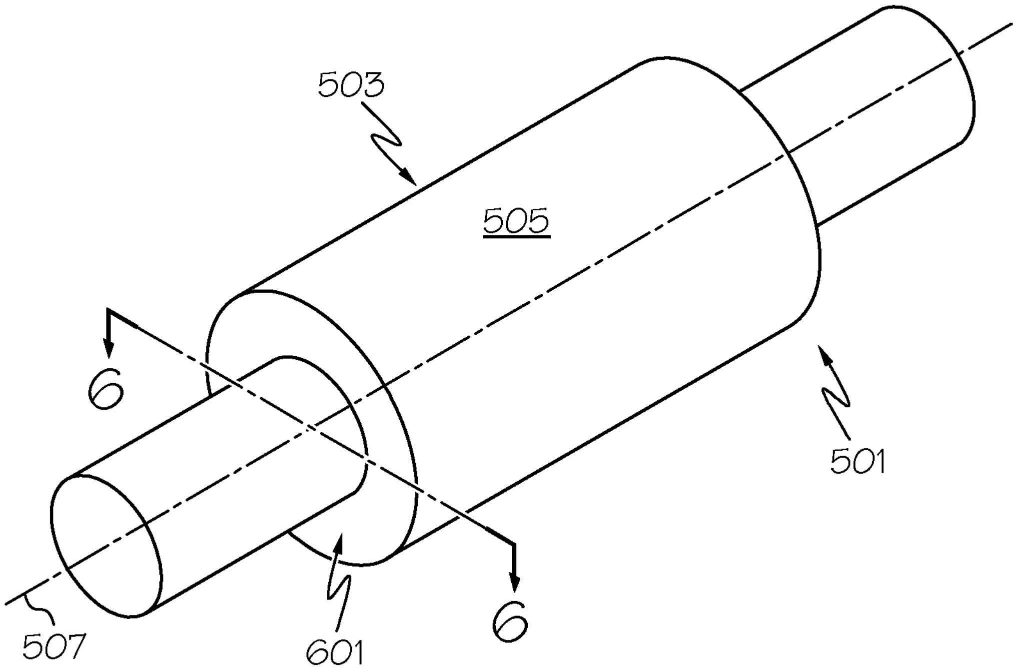
503
505
6
501
6
507
601

FIG. 5

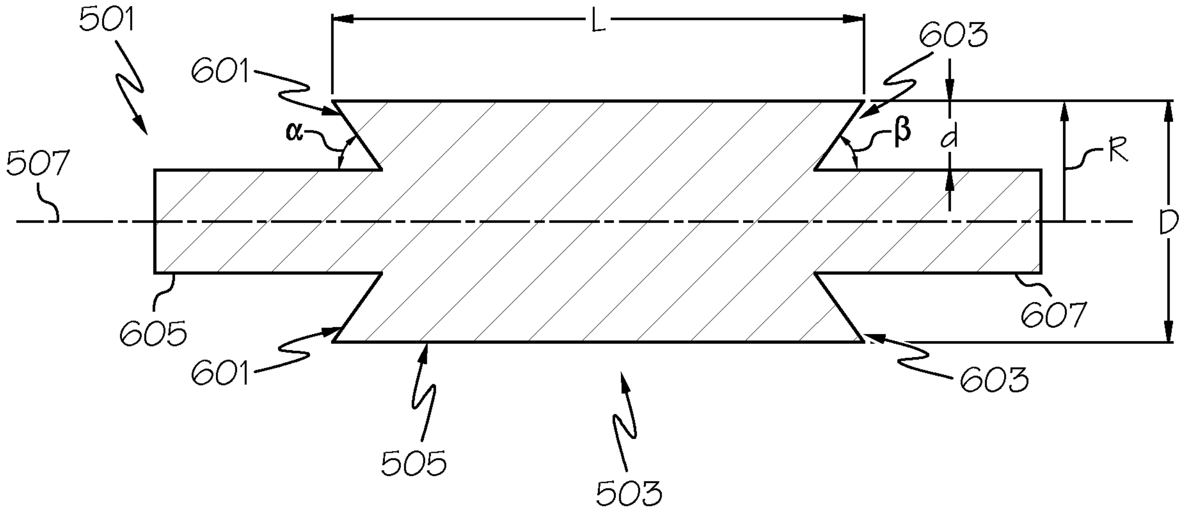
L
501
603
601
α
β
d
R
507
D
605
607
601
603
505
503

FIG. 6

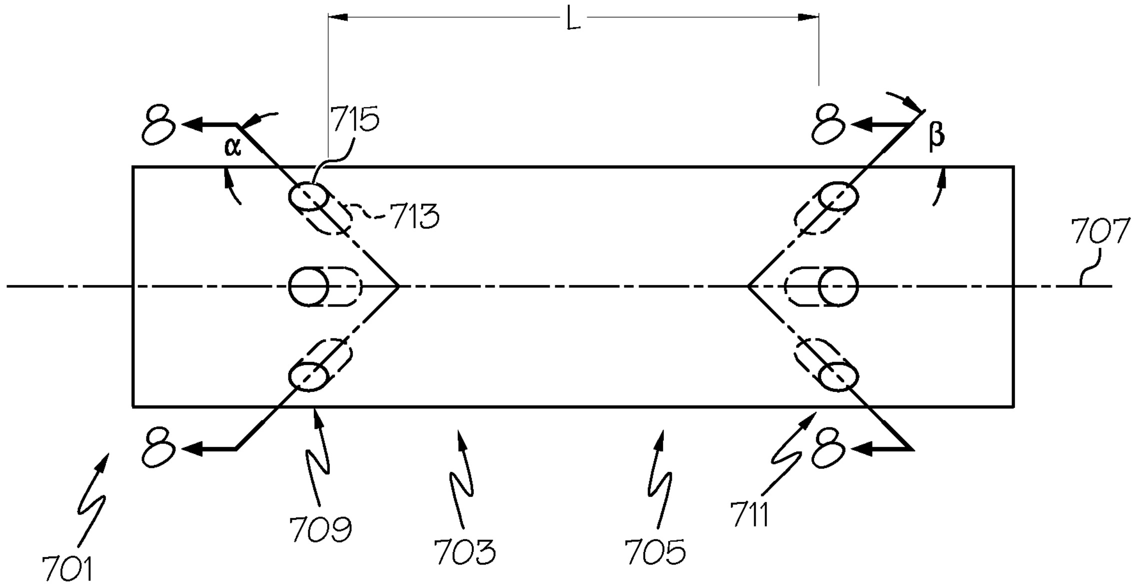


FIG. 7

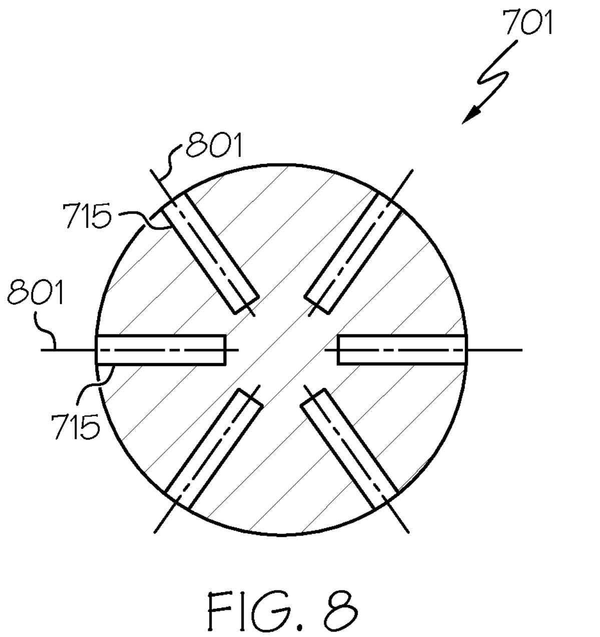


FIG. 8

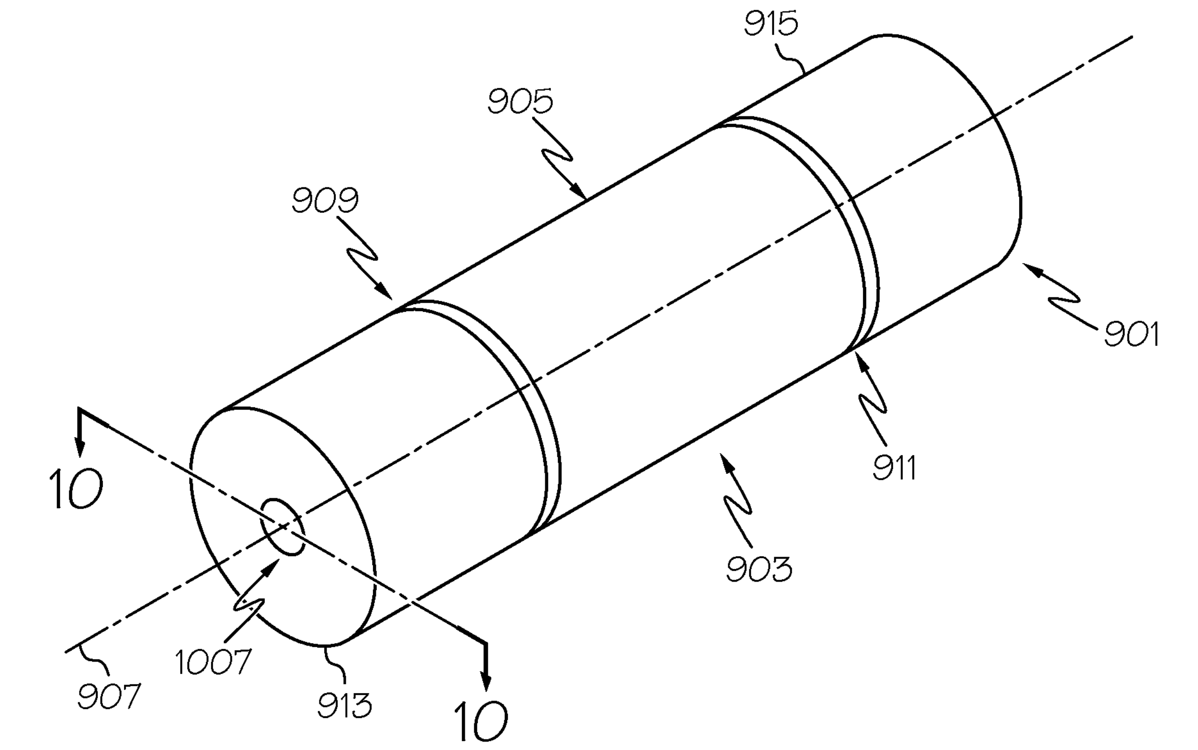
915
905
909
901
911
10
903
1007
907
913
10

FIG. 9

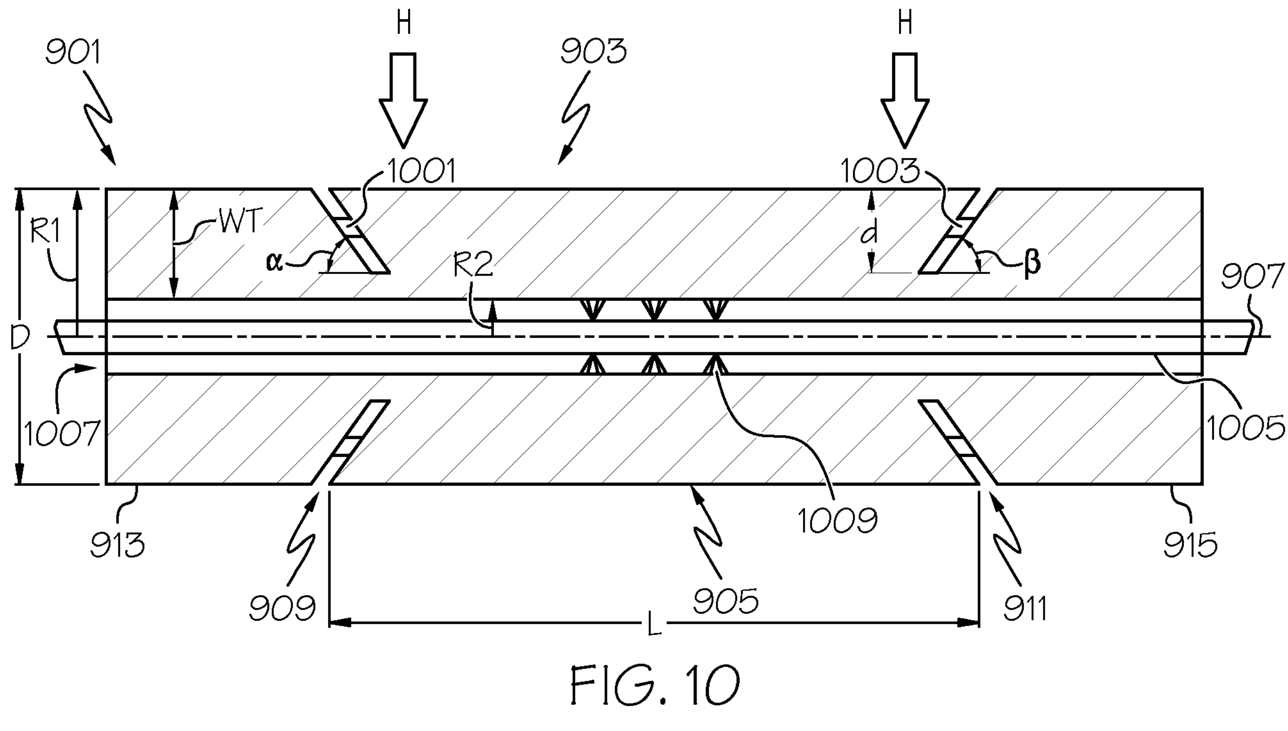
H
H
901
903
1001
1003
R1
WT
d
α
β
R2
907
D
1007
1005
913
1009
915
909
905
911
L

FIG. 10

# INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/046976

**A. CLASSIFICATION OF SUBJECT MATTER**
INV. C03B13/16 C03B13/04
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)
C03B B22D B21B C21D

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 1 659 053 A (SCHUTZ HAROLD R) 14 February 1928 (1928-02-14) | 1,2,5,7, 11-13, 16,17, 20,22-24 |
| | page 1, lines 27-48; figures 1-3<br>page 1, lines 84-94<br>page 2, lines 24-37<br>----- | |
| X | BE 357 209 A (CHARLES HEUZE) 28 February 1929 (1929-02-28)<br>page 1, line 1 - page 2, line 20; claim 1; figures 1,2<br>page 4, lines 4-8<br>----- | 1,4,7, 19,22,23 |
| A | US 3 655 355 A (TISSIER PIERRE) 11 April 1972 (1972-04-11)<br>column 1, lines 10-22,40-44; figure 4<br>column 2, lines 39-44<br>----- | 1,11,17 |

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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

"E" earlier 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 | Date of mailing of the international search report |
|---|---|
| 29 September 2014 | 07/10/2014 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040,<br>Fax: (+31-70) 340-3016 | Creux, Sophie |

# INTERNATIONAL SEARCH REPORT

| International application No |
|---|
| PCT/US2014/046976 |

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | WO 2012/166761 A1 (CORNING INC [US]; LAKOTA ALEXANDER [US]; LOCK WILLIAM EDWARD [US]; SCH) 6 December 2012 (2012-12-06) paragraphs [0004], [0005], [0011], [0012], [0021]; claims 1-5; figures 1,14,15<br>----- | 1,11,17 |

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2014/046976

| Patent document cited in search report | | Publication date | Patent family member(s) | | | Publication date |
|---|---|---|---|---|---|---|
| US 1659053 | A | 14-02-1928 | NONE | | | |
| BE 357209 | A | 28-02-1929 | NONE | | | |
| US 3655355 | A | 11-04-1972 | BE | 737987 | A | 26-02-1970 |
| | | | DE | 1943146 | A1 | 16-04-1970 |
| | | | ES | 370407 | A1 | 16-04-1971 |
| | | | FR | 1582950 | A | 10-10-1969 |
| | | | GB | 1241627 | A | 04-08-1971 |
| | | | NL | 6912441 | A | 03-03-1970 |
| | | | US | 3655355 | A | 11-04-1972 |
| WO 2012166761 | A1 | 06-12-2012 | CN | 103608305 | A | 26-02-2014 |
| | | | EP | 2714600 | A1 | 09-04-2014 |
| | | | JP | 2014520059 | A | 21-08-2014 |
| | | | KR | 20140027311 | A | 06-03-2014 |
| | | | TW | 201309603 | A | 01-03-2013 |
| | | | US | 2012304695 | A1 | 06-12-2012 |
| | | | WO | 2012166761 | A1 | 06-12-2012 |