CERAMIC FORMING DEVICES WITH A HONEYCOMB STRUCTURE AND METHODS

A ceramic forming device for fusion drawing a glass ribbon includes a honeycomb structure. In further examples, a method of making a ceramic forming device for fusion drawing a glass ribbon includes the step of extruding a ceramic-forming batch material through a die member to form a green body. The green body includes a plurality of walls that are formed to define a plurality of channels extending through the green body. Each of the plurality of walls has a thickness defined between a corresponding pair of the channels from about 0.5 mm to about 30 mm. The methods further include the step of firing the green body to form a fired ceramic body with the honeycomb structure. The methods further include the step of providing the ceramic forming device with a wedge and a trough at least partially defined by a pair of weirs, wherein the honeycomb structure forms at least a portion of the ceramic forming device.
CERAMIC FORMING DEVICES WITH A HONEYCOMB STRUCTURE AND METHODS

[0001] This application claims the benefit of priority of 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 61/529504 filed on August 31, 2011 the content of which is relied upon and incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] The present invention relates generally to ceramic forming devices and, more particularly, to ceramic forming devices including a honeycomb structure and methods.

BACKGROUND

[0003] Glass manufacturing apparatus are commonly used to form various glass products such as LCD sheet glass. It is known to manufacture sheet glass by downwardly flowing molten glass over a ceramic forming device and fusion drawing a glass ribbon from the ceramic forming device.

SUMMARY

[0004] 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.

[0005] In one example aspect of the disclosure, a ceramic forming device for fusion drawing a glass ribbon is provided. The ceramic forming device includes a forming wedge comprising a pair of downwardly inclined forming surface portions extending between opposed ends of the forming wedge. The pair of downwardly inclined forming surface portions each converging along a downstream direction to form a root of the forming wedge. A honeycomb structure forms at least a portion of the ceramic forming device with the honeycomb structure comprising a plurality of walls at least partially defining a plurality of channels.
In one embodiment of the aspect, the ceramic forming device further comprises a trough at least partially defined by a pair of weirs including a first weir and a second weir defining opposite sides of the trough.

In another embodiment of the aspect, the trough includes a depth between a top of at least one of the pair of weirs and a lower portion of the trough that varies along an axis of the ceramic forming device.

In still another embodiment of the aspect, the honeycomb structure forms at least a portion of the pair of weirs.

In yet another embodiment of the aspect, the honeycomb structure forms at least a portion of the forming wedge.

In another embodiment of the aspect, each of the plurality of walls of the honeycomb structure includes a thickness defined between a corresponding pair of channels from about 0.5 mm to about 30 mm, in certain embodiments at most 25 mm, in certain other embodiments at most 20 mm, in certain other embodiments at most 15 mm, in certain other embodiments at most 10 mm, in certain other embodiments at most 8 mm, in certain other embodiments at most 5 mm, in certain other embodiments at most 3 mm, in certain other embodiments at most 2 mm, in certain other embodiments at most 1 mm.

In still another embodiment of the aspect, the honeycomb structure has a channel density of about 1/25 channel/cm² to about 20 channels/cm², in certain embodiments at least 1/20 channel/cm², in certain embodiments at least 1/15 channel/cm², in certain embodiments at least 1/10 channel/cm², in certain embodiments at least 1/5 channel/cm², in certain embodiments at least 1/2 channel/cm², in certain embodiments at least 2 channels/cm², in certain embodiments at least 5 channels/cm², in certain embodiments at least 10 channels/cm², in certain embodiments at least 15 channels/cm².

In yet another embodiment of the aspect, the ceramic forming device further comprises an outer layer of refractory material positioned over a peripheral surface of the honeycomb structure.

In one embodiment of the aspect, the outer layer of refractory material comprises a ceramic material.
In still another embodiment of the aspect, the ceramic material of the outer layer comprises a closed-cell porous structure.

In another example aspect of the disclosure, a method of fusion drawing a glass ribbon comprising the step (I) of providing a ceramic forming device comprising a trough at least partially defined by a pair of weirs including a first weir and a second weir defining opposite sides of the trough. The ceramic forming device further includes a forming wedge comprising a pair of downwardly inclined forming surface portions extending between opposed ends of the forming wedge. The pair of downwardly inclined forming surface portions each converge along a downstream direction to form a root of the forming wedge. A honeycomb structure forms at least a portion of the ceramic forming device with the honeycomb structure comprising a plurality of walls at least partially defining a plurality of channels. The method further includes the step (II) of introducing glass melt into the trough of the ceramic forming device. The method still further includes the step (III) of spilling the molten glass from the trough over top edges of the pair of weirs such that corresponding molten glass sheets travel down the respective inwardly inclined forming surface portions. The method still further includes the step (IV) of fusion drawing the molten glass sheets together as a glass ribbon off the root of the forming wedge.

In one embodiment of the aspect, step (I) provides the honeycomb structure forming at least a portion of the pair of weirs.

In another embodiment of the aspect, step (I) provides the honeycomb structure forming at least a portion of the forming wedge.

In still another embodiment of the aspect, step (I) provides the honeycomb structure forming substantially the entire forming wedge.

In another embodiment of the aspect, step (I) provides an outer layer of refractory material positioned over a peripheral surface of the honeycomb structure forming the forming wedge.

In yet another embodiment of the aspect, step (I) provides an outer layer of refractory material positioned over a peripheral surface of the honeycomb structure.

In still another embodiment of the aspect, step (I) provides each of the plurality of walls of the honeycomb structure with a thickness defined between a
corresponding pair of channels from about 0.5 mm to about 30 mm, in certain embodiments at most 25 mm, in certain other embodiments at most 20 mm, in certain other embodiments at most 15 mm, in certain other embodiments at most 10 mm, in certain other embodiments at most 8 mm, in certain other embodiments at most 5 mm, in certain other embodiments at most 3 mm, in certain other embodiments at most 2 mm, in certain other embodiments at most 1 mm.

[0022] In another embodiment of the aspect, step (I) provides the honeycomb structure with a channel density of about 1/25 channel/cm² to about 20 channels/cm², in certain embodiments at least 1/20 channel/cm², in certain embodiments at least 1/15 channel/cm², in certain embodiments at least 1/10 channel/cm², in certain embodiments at least 1/5 channel/cm², in certain embodiments at least 1/2 channel/cm², in certain embodiments at least 1 channel/cm², certain embodiments at least 2 channels/cm², in certain embodiments at least 5 channels/cm², in certain embodiments at least 10 channels/cm², in certain embodiments at least 15 channels/cm².

[0023] In still example aspect of the disclosure, a method of making a ceramic forming device for fusion drawing a glass ribbon comprising the step of (I) extruding a ceramic-forming batch material through a die member to form a green body with a honeycomb structure including a plurality of walls at least partially defining a plurality of channels extending through the green body. Each of the plurality of walls has a thickness defined between a corresponding pair of the channels from about 0.5 mm to about 30 mm, in certain embodiments at most 25 mm, in certain other embodiments at most 20 mm, in certain other embodiments at most 15 mm, in certain other embodiments at most 10 mm, in certain other embodiments at most 8 mm, in certain other embodiments at most 5 mm, in certain other embodiments at most 3 mm, in certain other embodiments at most 2 mm, in certain other embodiments at most 1 mm. The method further includes the step of (II) firing the green body to form a fired ceramic body with the honeycomb structure. The method still further includes the step of (III) providing the ceramic forming device with a wedge and a trough at least partially defined by a pair of weirs, wherein the honeycomb structure forms at least a portion of the ceramic forming device.

[0024] In one embodiment of the aspect, step (III) includes using a machining process to provide the ceramic forming device.
[0025] In another embodiment of the aspect, the machining process of step (III) includes machining the green body before step (II).

[0026] In another embodiment of the aspect, the machining process of step (III) includes machining the fired ceramic body after step (II).

[0027] In another embodiment of the aspect, step (I) forms the honeycomb structure with a channel density of about 1/25 channel/cm\(^2\) to about 20 channel/cm\(^2\), in certain embodiments at least 1/20 channel/cm\(^2\), in certain embodiments at least 1/15 channel/cm\(^2\), in certain embodiments at least 1/10 channel/cm\(^2\), in certain embodiments at least 1/5 channel/cm\(^2\), in certain embodiments at least 1/2 channel/cm\(^2\), in certain embodiments at least 1 channel/cm\(^2\), in certain embodiments at least 2 channels/cm\(^2\), in certain embodiments at least 5 channels/cm\(^2\), in certain embodiments at least 10 channels/cm\(^2\), in certain embodiments at least 15 channels/cm\(^2\).

[0028] In another embodiment of the aspect, the honeycomb structure forms at least a portion of the wedge of the ceramic forming device.

[0029] In another embodiment of the aspect, the ceramic body includes a substantially closed-cell porous structure.

[0030] In another embodiment of the aspect, the method further comprises the step of preparing the ceramic-forming material by mixing a first quantity of particles having a first mean particle size with a second quantity of particles having a second mean particle size greater than the first mean particle size.

[0031] In another embodiment of the aspect, the first and second quantity of particles comprise alumina particles.

[0032] In another embodiment of the aspect, the first mean particle size of the first quantity of alumina particles is about 0.6 microns and the second mean particle size of the second quantity of alumina particles is about 2.7 microns.

[0033] In another embodiment of the aspect, the weight ratio of the first quantity of alumina particles to the second quantity of alumina particles is about 3:1.

[0034] In another embodiment of the aspect, the first and second quantity of particles comprise zircon particles.
In another embodiment of the aspect, the first mean particle size of the first quantity of zircon particles is about 1 micron and the second mean particle size of the second quantity of zircon particles is about 7 microns.

In another embodiment of the aspect, the weight ratio of the first quantity of zircon particles to the second quantity of zircon particles is about 1:1.

In another embodiment of the aspect, the method further comprises the step of applying an outer layer of refractory material to a peripheral surface of the honeycomb structure.

In another embodiment of the aspect, the method further comprises the step of reducing an oxygen level of an atmosphere in a firing chamber during step (II).

In another embodiment of the aspect, the method further comprises the step of forcing fluid through the plurality of channels during step (II).

In another embodiment of the aspect, the method further comprises the step of forcing steam through the plurality of channels during step (II).

In yet another example aspect of the disclosure, a method of making a ceramic forming device for fusion drawing a glass ribbon comprising the step of extruding a ceramic-forming batch material through a die member to form a green body with a honeycomb structure including a plurality of walls at least partially defining a plurality of channels extending through the green body, wherein each of the plurality of walls has a thickness defined between a corresponding pair of the channels from about 0.5 mm to about 30 mm, in certain embodiments at most 25 mm, in certain other embodiments at most 20 mm, in certain other embodiments at most 15 mm, in certain other embodiments at most 10 mm, in certain other embodiments at most 8 mm, in certain other embodiments at most 5 mm, in certain other embodiments at most 3 mm, in certain other embodiments at most 2 mm, in certain other embodiments at most 1 mm, and the honeycomb structure includes a channel density of about 1/25 channel/cm² to about 20 channels/cm², in certain embodiments at least 1/20 channel/cm², in certain embodiments at least 1/15 channel/cm², in certain embodiments at least 1/10 channel/cm², in certain embodiments at least 1/5 channel/cm², in certain embodiments at least 1/2 channel/cm², in certain embodiments at least 1 channel/cm², in certain embodiments at least 2 channels/cm², in certain embodiments at least 5 channels/cm², in
certain embodiments at least 10 channels/cm², in certain embodiments at least 15 channels/cm². The method further includes the step of machining the green body such that a green forming device is provided with a wedge and a trough at least partially defined by a pair of weirs, wherein the honeycomb structure forms at least a portion of the green forming device. The method further includes the step of firing the green forming device to form a fired ceramic forming device with the honeycomb structure. 

[0042] In still another example aspect of the disclosure, a method of making a ceramic forming device for fusion drawing a glass ribbon comprising the step of extruding a ceramic-forming batch material through a die member to form a green body with a honeycomb structure including a plurality of walls at least partially defining a plurality of channels extending through the green body. Each of the plurality of walls has a thickness defined between a corresponding pair of the channels from about 0.5 mm to about 30 mm, in certain embodiments at most 25 mm, in certain other embodiments at most 20 mm, in certain other embodiments at most 15 mm, in certain other embodiments at most 10 mm, in certain other embodiments at most 8 mm, in certain other embodiments at most 5 mm, in certain other embodiments at most 3 mm, in certain other embodiments at most 2 mm, in certain other embodiments at most 1 mm, and the honeycomb structure includes a channel density of about 1/25 channel/cm² to about 20 channels/cm², in certain embodiments at least 1/20 channel/cm², in certain embodiments at least 1/15 channel/cm², in certain embodiments at least 1/10 channel/cm², in certain embodiments at least 1/5 channel/cm², in certain embodiments at least 1/2 channel/cm², in certain embodiments at least 1 channel/cm², in certain embodiments at least 2 channels/cm², in certain embodiments at least 5 channels/cm², in certain embodiments at least 10 channels/cm², in certain embodiments at least 15 channels/cm². The method further includes the step of firing the green body to form a fired ceramic body with the honeycomb structure. The method further includes the step of machining the fired ceramic body such that the ceramic forming device is provided with a wedge and a trough at least partially defined by a pair of weirs, wherein the honeycomb structure forms at least a portion of the ceramic forming device.
BRIEF DESCRIPTION OF THE DRAWINGS

[0043] These and other aspects are better understood when the following detailed description is read with reference to the accompanying drawings, in which:

[0044] FIG. 1 is a schematic view of a fusion draw apparatus including a ceramic forming device in accordance with aspects of the disclosure;

[0045] FIG. 2 is a sectional enlarged perspective view of the ceramic forming device of FIG. 1;

[0046] FIG. 3 is an enlarged view of the honeycomb structure and outer layer of FIG. 2;

[0047] FIG. 4 is an enlarged view of the closed porous structure of the fired ceramic material;

[0048] FIG. 5 is a schematic view illustrating an extrusion process for extruding a ceramic-forming batch material through a die member to form a green body;

[0049] FIG. 6 illustrates an example particle distribution of a first quantity of alumina particles and a second quantity of alumina particles;

[0050] FIG. 7 illustrates a calculated distribution and an actual distribution of a combination of the first quantity of alumina particles and the second quantity of alumina particles of FIG. 6;

[0051] FIG. 8 is an enlarged partial sectional view of a portion of the die member of FIG. 5;

[0052] FIG. 9 is a sectional view of a segmented green body along line 9-9 of FIG. 5;

[0053] FIG. 10 illustrates a method of firing the green body to form a fired ceramic body;

[0054] FIG. 11 illustrates an example firing cycle for firing the green body to form a fired ceramic body;

[0055] FIG. 12 schematically illustrates a process of machining that provides the honeycomb structure with a peripheral shape that approximates the outer peripheral shape of the weirs, trough and forming wedge of the ceramic forming device; and

[0056] FIG. 13 illustrates an outer layer of refractory material applied to the machined surfaces of the honeycomb structure.
DETAILED DESCRIPTION

[0057] 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.

[0058] FIG. 1 illustrates a schematic view of a fusion draw apparatus 101 for fusion drawing a glass ribbon 103 for subsequent processing into glass sheets. The fusion draw apparatus 101 can include a melting vessel 105 configured to receive batch material 107 from a storage bin 109. The batch material 107 can be introduced by a batch delivery device 111 powered by a motor 113. An optional controller 115 can be configured to activate the motor 113 to introduce a desired amount of batch material 107 into the melting vessel 105, as indicated by arrow 117. A glass metal probe 119 can be used to measure a glass melt 121 level within a standpipe 123 and communicate the measured information to the controller 115 by way of a communication line 125.

[0059] The fusion draw apparatus 101 can also include a fining vessel 127, such as a fining tube, located downstream from the melting vessel 105 and coupled to the melting vessel 105 by way of a first connecting tube 129. A mixing vessel 131, such as a stir chamber, can also be located downstream from the fining vessel 127 and a delivery vessel 133, such as a bowl, may be located downstream from the mixing vessel 131. As shown, a second connecting tube 135 can couple the fining vessel 127 to the mixing vessel 131 and a third connecting tube 137 can couple the mixing vessel 131 to the delivery vessel 133. As further illustrated, a downcomer 139 can be positioned to deliver glass melt 121 from the delivery vessel 133 to an inlet 141 of a ceramic forming device 143. As shown, the melting vessel 105, fining vessel 127, the mixing vessel 131, delivery vessel 133, and ceramic forming device 143 are examples of glass melt stations that may be located in series along the fusion draw apparatus 101.

[0060] The melting vessel 105 is typically made from a refractory material, such as refractory (e.g. ceramic) brick. The fusion draw apparatus 101 may further include components that are typically made from platinum or platinum-containing metals such as platinum-rhodium, platinum-iridium and combinations thereof, but which may also
comprise such refractory metals such as molybdenum, palladium, rhenium, tantalum, titanium, tungsten, ruthenium, osmium, zirconium, and alloys thereof and/or zirconium dioxide. The platinum-containing components can include one or more of the first connecting tube 129, the fining vessel 127 (e.g., finer tube), the second connecting tube 135, the standpipe 123, the mixing vessel 131 (e.g., a stir chamber), the third connecting tube 137, the delivery vessel 133 (e.g., a bowl), the downcomer 139 and the inlet 141.

The ceramic forming device 143 is made from a ceramic material and is designed to form the glass ribbon 103.

[0061] FIG. 2 is a cross-sectional perspective view of the fusion draw apparatus 101 along line 2-2 of FIG. 1. As shown, the ceramic forming device 143 can include a trough 201 at least partially defined by a pair of weirs comprising a first weir 203 and a second weir 205 defining opposite sides of the trough 201. As further shown, the trough may also be at least partially defined by a bottom wall 207. As shown, the inner surfaces of the weirs 203, 205 and the bottom wall 207 define a substantially U shape with the surfaces located substantially 90° relative to one another. In further examples, the U shape may have rounded corners. In still further examples, the trough may have a bottom surface defined by an intersection of the inner surfaces of the weirs 203, 205. For example, the trough may have a V-shaped profile. Although not shown, the trough can include further configurations in additional examples.

[0062] As shown, the trough 201 can have a depth "D" between a top of the weir and a lower portion of the trough 201 that varies along an axis 209 although the depth may be substantially the same along the axis 209. Varying the depth "D" of the trough 201 may facilitate consistency in glass ribbon thickness across the width of the glass ribbon. In just one example, as shown in FIG. 2, the depth "Di" near the inlet of the ceramic forming device 143 can be greater than the depth "D2" of the trough 201 at a location downstream from the inlet of the trough 201. As demonstrated by the dashed line 210, the bottom wall 207 may extend at an acute angle relative to the axis 209 to provide a substantially continuous reduction in depth along a length of the ceramic forming device 143 from the inlet end to the opposite end.

[0063] The ceramic forming device 143 further includes a forming wedge 211 comprising a pair of downwardly inclined forming surface portions 213, 215 extending
between opposed ends of the forming wedge 211. The pair of downwardly inclined forming surface portions 213, 215 each converges along a downstream direction 217 to form a root 219. A draw plane 221 extends through the root 219 wherein the glass ribbon 103 may be drawn in the downstream direction 217 along the draw plane 221. As shown, the draw plane 221 can bisect the root 219 although the draw plane 221 may extend at other orientations with respect to the root 219.

[0064] The ceramic forming device 143 may optionally be provided with one or more edge directors 223 intersecting with at least one of the pair of downwardly inclined forming surface portions 213, 215. In further examples, the one or more edge directors can intersect with both downwardly inclined forming surface portions 213, 215. In further examples, an edge director can be positioned at each of the opposed ends of the forming wedge 211 wherein an edge of the glass ribbon 103 is formed by molten glass flowing off the edge director. For instance, as shown in FIG. 2, the edge director 223 can be positioned at a first opposed end 225a and a second identical edge director (not shown) can be positioned at a second opposed end (see 225b in FIG. 1). Each edge director can be configured to intersect with both of the downwardly inclined forming surface portions 213, 215. Each edge director 223 can be substantially identical to one another although the edge directors may have different characteristics in further examples. Various forming wedge and edge director configurations may be used in accordance with aspects of the present disclosure. For example, aspects of the present disclosure may be used with forming wedges and edge director configurations disclosed in U.S. Pat. No. 3,451,798, U.S. Patent No. 3,537,834, U.S. Patent No. 7,409,839 and/or U.S. Provisional Pat. Application No. 61/155,669, filed February 26, 2009 that are each herein incorporated by reference in its entirety.

[0065] The ceramic forming device 143 can comprise a wide range of ceramic compositions that have material properties that are suitable for fusion drawing molten glass into a glass ribbon. Typical material characteristics can comprise resistance to high temperatures without contaminating the molten glass, strength, the ability to avoid creep, resistance to wear and/or other features. In some examples the ceramic forming device is formed from zircon, alumina, xenotime, or other ceramic materials. In further examples, the ceramic composition can be fired into a cordierite body.
As shown in FIG. 2, at least a portion of the ceramic forming device 143 can comprise a honeycomb structure 227 with a plurality of walls 229 at least partially defining a plurality of channels 231. As shown, the honeycomb structure 227 can include a lattice of intersecting walls forming a honeycomb network of channels. In one example, the channels can substantially extend along the axis 209 that is included in the draw plane 221. As shown, the channels 231 can extend along the axis 209 in a direction that is substantially parallel to the draw plane 221 although the channels 231 may helically twist along the axis 209 in further examples. Still further, additional examples may include channels 231 that extend at other directions. For example, the channels may extend angularly with respect to the axis 209. In further examples, the channels 231 may extend substantially perpendicular to the draw plane 221 although the channels may extend at other angles in further examples.

By way of illustration, FIG. 3 shows an example honeycomb structure 227 with the channels 231 being substantially identical to one another and evenly spaced from one another. In further examples, the channels 231 may be spaced differently from one another and/or may have different sizes and/or shapes. As shown, the shape of the channels 231 can be substantially square although the cells can include other polygonal shapes with three or more sides (e.g., triangular, rectangular, pentagon, hexagon, heptagon, octagon, etc.) circular, oval or other shape configurations. While FIG. 3 shows the channels with relatively sharp corners, it is also possible to fillet these corners to increase the strength of the honeycomb.

As further shown in FIG. 3, the honeycomb structure 227 can include a channel density that can be considered the average number of channels of the honeycomb structure that are intersected by a cross sectional plane taken perpendicular to the axis 209 and the draw plane 221. The plurality of walls 229 of the honeycomb structure also has a thickness "T" that is considered the average thickness of the channels between each corresponding pair of channels 231. As shown, the thickness "T" of the walls 229 can be substantially identical to one or more walls may have different thicknesses in further examples.

The channel density and thickness "T" can be adjusted to provide a wide range of benefits. For example, the channel density and thickness "T" can be adjusted to
reduce the time to fire the green body into the ceramic body during the firing process. Indeed, the channels can enhance heat transfer quickly to interior areas of the green body. The temperature may therefore be raised faster without developing undesirable thermal gradients that may otherwise crack the forming device during the firing process. Moreover, as discussed below, the size of the channels and the channel density can be selected to allow efficient movement of fluid through the channels. Still further, the channel density and thickness can be adjusted to provide optimal creep resistance, strength, machining ease and other factors.

[0070] In further examples, the channel density and thickness "T" can be adjusted to reduce the weight of the ceramic forming device 143. A reduced weight can help facilitate transport of the ceramic forming device 143, reduce effort and resources in transporting the ceramic forming device to the site location, as well as simplify manipulation of the ceramic forming device 143 into position in the fusion draw apparatus 101. Still further, reducing the weight of the ceramic forming device 143 can help reduce bending moments that may result in deformation of the ceramic forming device 143 in use. Still further, the reduced weight can help the ceramic forming device 143 resist undesirable thermal deformation (e.g., thermal creep). Still further, the channel density and thickness "T" can be selected to provide the ceramic forming device 143 with sufficient strength to avoid deformation in use. For example, the lattice of intersecting walls can help formulate the ceramic forming device 143 with sufficient strength while taking advantage of reduced firing time, reduced weight and other beneficial features of the honeycomb structure 227. It may also be desirable to make the channel wall thickness "T" non-uniform across the honeycomb cross-section. For example, it may important to make the channel wall thickness "T" larger near the perimeter for increased skin strength and thermal conductivity. Alternatively, it may be desirable to make the channel walls thicker for vertically-oriented walls thicker than for horizontally-oriented walls. This approach can be used to reduce bending moments that may result in deformation of the ceramic forming device in use, while minimizing the total weight of the device. The same approach may also be used to establish a preferred direction for heat transfer into or out of the device during thermal processing. For example, during binder burnout two- and three-dimensional thermal gradients can develop near substrate
corners that induce shrinkage cracks. By establishing a preferred direction for heat transfer within the substrate, thermal gradients may be established within the substrate during binder burnout along a single axis, allowing substrate material to shrink along the axis direction without cracking. External refractory insulating materials may also be required around the substrate during this binder burnout to maintain the one-dimensional thermal gradient.

[0071] In some examples, the cell density can be from about 1/25 channel/cm$^2$ to about 20 channels/cm$^2$, in certain embodiments at least 1/20 channel/cm$^2$, in certain embodiments at least 1/15 channel/cm$^2$, in certain embodiments at least 1/10 channel/cm$^2$, in certain embodiments at least 1/5 channel/cm$^2$, in certain embodiments at least 1/2 channel/cm$^2$, in certain embodiments at least 1 channel/cm$^2$, in certain embodiments at least 2 channels/cm$^2$, in certain embodiments at least 5 channels/cm$^2$, in certain embodiments at least 10 channels/cm$^2$, in certain embodiments at least 15 channels/cm$^2$. Byway of example, FIG. 3 shows one example of a square area of the honeycomb cell structure 227 with sides having a length "L". In one example, the length "L" can be 1 cm although other lengths may be used in further example. As shown, 16 channels are located within the one square cm. As such, if the illustrated square area is representative of the entire area of the honeycomb structure 227, the illustrated cell density is 16 channels/cm$^2$. In other examples, the channel density can be greater than 1 channel/cm$^2$ or less than 20 channels/cm$^2$ depending on the application, such as less than 19 channels/cm$^2$. In addition, or alternatively, the thickness "T" can be from about 0.5 mm (i.e., about 0.02 inches) to about 30 mm, in certain embodiments at most 25 mm, in certain other embodiments at most 20 mm, in certain other embodiments at most 15 mm, in certain other embodiments at most 10 mm, in certain other embodiments at most 8 mm, in certain other embodiments at most 5 mm, in certain other embodiments at most 3 mm, in certain other embodiments at most 2 mm, in certain other embodiments at most 1 mm, although other thicknesses may be used in further examples.

[0072] In further examples the cross section of the honeycomb structure 227 along a plane taken perpendicular to the channels can present a honeycomb structure including a C/F ratio of total channel area ("C") with respect to the total footprint area ("F") of the honeycomb structure (i.e., including the total cross sectional area of the walls and the
channels). In such examples, the C/F ratio can be from about 0.25 to about 0.80 although other ratios may be used in further examples.

[0073] As shown in FIGS. 2 and 3, the ceramic forming device 143 can also include an optional outer layer 233. Referring to FIG. 3, the outer layer 233, if provided, can be applied to provide a smooth surface 301 configured to allow molten glass to flow uninterrupted. As such, the outer layer 233 can be applied over a machined outer periphery 303 to be applied over outer machined edges 305 of the walls 229 and/or within partial channels 307 that may be exposed during a machining process. In one example, the outer layer 233 can be formed from the same or similar material as the honeycomb structure 227. In addition, or alternatively, the materials for the outer layer 233 and the honeycomb structure 227 can be selected to have a similar or identical coefficient of thermal expansion.

[0074] FIG. 4, shows an example schematic interior structure of a fired ceramic material 401 that can be considered to represent the material of the walls 229 and/or the outer layer 233. As shown, the fired ceramic material 401 includes a porous material including closed pores 403. As such, the ceramic material includes a substantially closed-cell porous structure. The closed porosity of the fired ceramic material 401 can help minimize unwanted permutation of molten glass into the ceramic forming device. The process parameters and/or batch ingredients of the ceramic-forming material can be adjusted such that the pores have a median pore size of, for example, less than about 100 microns, less than about 50 microns, or less than about 25 microns.

[0075] The honeycomb structure 227 can be used to form at least a portion of the forming wedge 211 and/or the weirs 203, 205. For instance, the honeycomb structure can form at least a portion of forming wedge 211. In addition or alternatively, the honeycomb structure 227 can form at least a portion of the weirs 203, 205. As such, the honeycomb structure may be used to form only parts of the ceramic forming device 143. In further examples, as shown, the honeycomb structure 227 may form substantially the entire ceramic forming device 143 although further examples the honeycomb structure 227 may form all of the ceramic forming device 143. Indeed, as shown, the honeycomb structure forms substantially the entire forming wedge 211 and weirs 203, 205.
Method of making glass ribbon with the fusion draw apparatus 101 will now be discussed with initial reference to FIG. 1. First, batch material 107 can be introduced from the storage bin 109. The controller 115 activates the motor 113 such that the batch material 107 is conveyed into the melting vessel 105 as indicated by arrow 117. The batch material is then melted into glass melt 121 within the melting vessel 105. The glass melt 121 then passes through the first connecting tube 129 to enter the fining vessel 127 wherein gas bubbles may be removed from the glass melt 121. The glass melt then passes through the second connecting tube 135 to enter the mixing vessel 131. The mixing vessel 131 is operated to mix the glass melt 121 to provide a homogeneous mixture. The glass melt then passes through the third connecting tube 137 and into the delivery vessel 133 and thereafter delivered into the inlet 141 of the ceramic forming device 143 by way of the downcomer 139.

Turning to FIG. 2, the glass melt 121 travels into the trough 201 and then spills over the top edges of the weirs 203, 205. Corresponding molten glass sheets then travel down the respective inwardly inclined forming surfaces 213, 215 of the forming wedge 211 with the edges of the molten glass sheets eventually flowing over the edge directors 223 as the molten glass sheets travel to the root 219 of the forming wedge 211. The two molten glass sheets are then fused together at the root 219 and draw off the root 219 as the glass ribbon 103.

The honeycomb structure 227 associated with the ceramic forming device 143 may significantly reduce the overall weight of the forming device 143. At the same time, walls 229 of the honeycomb structure 227 can be designed to provide the required structural support necessary to support the molten glass within the trough 201 and flowing down the downwardly including forming surfaces 213, 215. The reduction in weight due to the honeycomb structure 227 can help prevent undesirable bending of the ceramic forming device 143 that may occur due to the high operating temperatures. Indeed, the ceramic forming device 143 may be suspended by two opposed ends 225a, 225b wherein bending at the central portion of the ceramic forming device 143 may occur due to the weight of the forming device 143. The honeycomb structure 227 can provide sufficient force to resist such bending while the reduced weight further reduces the tendency of the ceramic forming device 143 to bend under its own weight. Moreover,
creep of the forming device 143 under the high temperature conditions may be avoided due to the reduction of the weight in the forming device 143 with the sufficient support features provided by the honeycomb structure 227.

[0079] Methods of making a ceramic forming device 143 for fusion drawing the glass ribbon 103 will now be described. The method can include the step of preparing a ceramic-forming batch material represented by step 501 in FIG. 5. Various ceramic-forming batch materials and/or compositions may be used in various examples. In one example, the batch composition can comprise zircon or alumina particles. In one example, particles can be provided in different quantities having different mean particle sizes to obtain desirable packing of the particles. For example, the method of preparing the batch of ceramic-forming batch material can comprise mixing a first quantity of alumina particles having a first mean particle size with a second quantity of alumina particles having a second mean particle size greater than the first mean particle size. In such examples, better packing can be achieved with a relatively larger quantity of smaller particles filling in the gaps occurring between a relatively smaller quantity of larger particles engaging one another.

[0080] In one example, alumina particles can be used as the ceramic-forming batch material. Alumina can be desirable, for example, since the material is compatible with numerous glasses without contaminating the glass melt as it passes over the ceramic forming device 143 during the fusion draw process. Alumina provides a relatively strong ceramic forming device 143 and is capable of operating at 1200 °C without creep deformation for extended periods of time. Alumina particles are commercially available from numerous suppliers and are relatively inexpensive - thereby reducing manufacturing costs.

[0081] The alumina particles can be selected to provide satisfactory performance of the ceramic forming device 143 based on an extrusion of the ceramic-forming material prior to firing into a ceramic forming device 143. The alumina particle distribution can be controlled to produce a microstructure where pores are closed so that glass does not easily penetrate the body and reduce the creep resistance. As such, the size of the grains after sintering can be controlled to have minimal, if any, micro-cracking for optimum strength or controlled micro-cracking for optimum toughness.
FIG. 6 illustrates just one example particle comparison a particle distribution between a first quantity of alumina particles "A" and a particle distribution of a second quantity of alumina particles "B." The horizontal axis of FIG. 6 represents the size of the particles in microns while the vertical axis represents the volume percentage of the particles. The illustrated particle distributions were obtained by measuring with a light scattering particle size analyzer. The illustrated first quantity of alumina particles "A" was determined to have a first mean particle size of about 0.6 microns and the second quantity of alumina particles "B" was determined to have a second mean particle size of about 2.7 microns.

Calculations of particle packing using methods described by Funk and Dinger (D.R. Dinger, Dinger Ceramic Consulting Services, Clemson, SC) determined that optimal proportioning of the first quantity of particles "A" with the second quantity of particles "B" would result in the combined optimum particle distribution shown in FIG. 7. The horizontal axis of FIG. 7 represents the size of the particles in microns while the vertical axis represents the volume percentage of the particles. A first quantity of particles "A" was mixed with the second quantity of particles "B" at a ratio of 3:1. The resulting actual combined particle distribution was examined. As shown in FIG. 7, the actual combined particle distribution with the 3:1 ratio closely matches the optimum packing particle distribution 701.

The batch composition was then prepared that was subsequently fired to yield a substantially pure alumina forming device after sintering that is believed to be highly resilient to glass dissolution, good creep resistance at 1200 °C and have high static fatigue lifetime. As shown in the batch composition in Table 1 below, no inorganic sintering aids were included in the batch. It is also noted that the first quantity of particles "A" and the second quantity of particles "B" where sieved through a 100 mesh screen prior to extrusion to remove any large impurities.
Table 1 - Example alumina batch composition

<table>
<thead>
<tr>
<th>Material</th>
<th>Arbitrary Weight</th>
<th>Percent Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Quantity of Particles A</td>
<td>75</td>
<td>71.43%</td>
</tr>
<tr>
<td>Second Quantity of Particles B</td>
<td>25</td>
<td>23.81%</td>
</tr>
<tr>
<td>Methocel</td>
<td>5</td>
<td>4.76%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>105</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Liquid Super Additions</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Oleic Acid</td>
<td>2</td>
<td>2.00%</td>
</tr>
<tr>
<td>Water</td>
<td>9.2</td>
<td>9.20%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>116.2</strong></td>
<td>-</td>
</tr>
</tbody>
</table>

[0085] In further examples, zircon can be used rather than alumina. In such examples it was found that a mixture of 50% by weight of zircon particles with a median particle size of 7 microns and 50% by weight of zircon with median particle size of 1 micron sinter well to a very dense body without additional sintering aids.

[0086] FIG. 5 illustrates a schematic view of an extruder apparatus 503 configured to extrude a green body 505. The extrusion process can be desirable to produce a green body of potentially unlimited length, thereby allowing formation of very large ceramic forming devices that may prove difficult to produce with other conventional techniques. The illustrated extruder depicts a twin-screw extruder including twin screws 507a, 507b configured to be rotated by motors to mix and compress the batch of ceramic-forming material as it travels along direction 509 toward a die member 511. It is also possible to employ tandem extrusion techniques to form green bodies with larger cross-sectional dimensions.

[0087] FIG. 8 is an enlarged cross sectional view of an example die member 511 that may be used in accordance with aspects of the disclosure. As shown, the die member 511 includes feed holes 801 configured to feed batch material in direction 803 toward a plurality of die pins 805. The die pins are spaced apart from one another to define slots 807 designed to form the walls 229 of the honeycomb structure 227 as the batch material is drawn into the green body 505. The die pins 805 shown in FIG. 8 can have a square shape to define square-shaped channels 231 although other die pin configurations can be selected depending on the desired channel configuration. Moreover, in some examples, the corners of the die pins may be rounded to create rounded corners in the channels 231. Rounded corners can help reduce cracking that may occur when firing the green body.
As such, as shown in FIG. 5, the ceramic-forming batch material can be extruded through die member 511 as a continuous member of many alternative lengths. As such, the extrusion technique can be useful to produce ceramic forming devices 143 of various alternative lengths depending on the particular application. Once the desired length is achieved, a cutter 513 can be moved in direction 515 to sever the extruded green body 505 at sever location 517 to provide a segmented green body 519. As shown in FIG. 9, the segmented green body 519 can include the honeycomb structure 227 with the plurality of walls 229 at least partially defining the plurality of channels 231 extending through the green body.

In one example, the method can include the step of drying the green body 519 and then firing the green body 519 to form a fired ceramic body with the honeycomb structure 227. Drying can be achieved, for example, with a radio frequency drier ("RF drier") or other drying apparatus. FIGS. 10 and 11 illustrate just one example of firing the dried green ceramic body into the fired ceramic body. As shown, the dried green body 519 can be placed in a firing chamber 1001 having a heating mechanism 1003. The dried green body can optionally be placed in a horizontal orientation with the channels 231 oriented horizontally. In one example, the dried green body 519 can be placed on a refractory cradle 1005 with alumina sand 1007 or alumina beads so that the isopipe is free to move as it shrinks during sintering.

The green body 519 can then be fired to form a fired ceramic body with the honeycomb structure. An example firing cycle is found in Table 2 below that is also represented in FIG. 11 wherein the horizontal axis of FIG. 11 is the firing time in hours and the vertical axis is the temperature in degrees Celsius.
Table 2 - Sample Firing Cycle for Alumina Green Body

<table>
<thead>
<tr>
<th>Segment #</th>
<th>Segment Length (hours)</th>
<th>Set point (°C)</th>
<th>Total time (hours)</th>
<th>Total time (days)</th>
<th>Ramp rate (°C/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1101</td>
<td>10.8</td>
<td>180</td>
<td>10.8</td>
<td>0.45</td>
<td>16.67</td>
</tr>
<tr>
<td>1102</td>
<td>15</td>
<td>180</td>
<td>25.8</td>
<td>1.08</td>
<td>0</td>
</tr>
<tr>
<td>1103</td>
<td>7.2</td>
<td>300</td>
<td>33</td>
<td>1.38</td>
<td>16.67</td>
</tr>
<tr>
<td>1104</td>
<td>25.2</td>
<td>600</td>
<td>58.2</td>
<td>2.43</td>
<td>11.9</td>
</tr>
<tr>
<td>1105</td>
<td>21</td>
<td>1300</td>
<td>79.2</td>
<td>3.3</td>
<td>33.33</td>
</tr>
<tr>
<td>1106</td>
<td>3</td>
<td>1400</td>
<td>82.2</td>
<td>3.43</td>
<td>33.33</td>
</tr>
<tr>
<td>1107</td>
<td>4.5</td>
<td>1500</td>
<td>86.7</td>
<td>3.61</td>
<td>22.22</td>
</tr>
<tr>
<td>1108</td>
<td>8</td>
<td>1600</td>
<td>94.7</td>
<td>3.95</td>
<td>12.5</td>
</tr>
<tr>
<td>1109</td>
<td>5.4</td>
<td>1650</td>
<td>10.1</td>
<td>4.17</td>
<td>9.26</td>
</tr>
<tr>
<td>1110</td>
<td>8</td>
<td>1700</td>
<td>108.1</td>
<td>4.5</td>
<td>6.25</td>
</tr>
<tr>
<td>1111</td>
<td>4</td>
<td>1700</td>
<td>112.1</td>
<td>4.67</td>
<td>0</td>
</tr>
<tr>
<td>1112</td>
<td>25.12</td>
<td>20</td>
<td>137.2</td>
<td>5.72</td>
<td>-66.88</td>
</tr>
</tbody>
</table>

[0091] As shown in FIG. 11, the firing cycle includes four phases. Phase 1113 is the binder burn-out phase from about 20-600 °C. During phase 1113, the binder is burned out of the green body. Phase 1115 is the ramp phase from about 600-1300 °C. During the ramp phase, the temperature of the green body is brought to the sintering temperature. Phase 1117 is the sintering phase from about 1300-1700 °C. During the sintering phase, the green body is sintered into the fired ceramic body. Phase 1119 is the cool down phase from about 1700-20 °C. During the cool down phase, the fired ceramic body is brought down to room temperature. Once the sintering process is complete, the fired ceramic body can include a closed-porous alumina wall structure as shown schematically in FIG. 4.

[0092] The method can further comprising the step of reducing an oxygen level of an atmosphere in a firing chamber 1001. For example, as shown in FIG. 10, a canister 1008 of inert gas can be used to displace oxygen within the firing chamber 1001. Reducing the oxygen level of the atmosphere in the firing chamber can help control temperature fluctuations, for example, as the binder is burned out.

[0093] In addition, or alternatively, the method can further include the step of forcing fluid 1011, such as the reduced oxygen atmosphere, through the plurality of channels during the step of firing. In one example, the oxygen level is reduced below
normal atmospheric levels, and in further examples, below normal combustion of green body components. In one example, the oxygen level can be less than or equal to 6%.

[0094] As shown in FIG. 10, a device 1009 can be used to guide, such as force, the fluid 1011 through the channels 231 as indicated by directional arrows 1013. In some examples, the fluid can comprise air, N₂, air plus gas kiln combustion products, H₂O, etc., or other fluids. As shown schematically by the water droplets in FIG. 10, the fluid 1011 can comprise steam although the fluid 1011 can comprise gas that is substantially free of moisture in further examples. Use of steam as the fluid can help reduce the sintering times (e.g., 48 hours) when compared to sintering times (e.g., 4-6 days) for air sintering. Moreover, it has been observed that steam sintered ceramic forming devices can shrink less than air sintered ceramic forming devices.

[0095] The channels 231 themselves and, if provided, the step of guiding such as forcing fluid through the channels 231 can facilitate heat transfer to the entire mass of the ceramic-forming material relatively fast. Indeed, the time for diffusion of the heat and gasses scales as the thickness of the body squared. The more channels within the body, the thinner the effective heat and gas diffusion distance. As such, channels (and optionally guiding fluid through the channels) together with walls having a reduced thickness between the channels can reduce the firing cycle time when compared to methodologies that fire the forming device without channels. The channels can also lead to more uniform firing conditions, thereby providing more uniform properties in even relatively large ceramic forming devices.

[0096] The method of making the ceramic forming device further includes the honeycomb structure forming at least a portion of the ceramic forming device 143. A wide range of techniques can provide the honeycomb structure as forming at least a portion of the ceramic forming device. For example, the extruded body itself, without substantial machining, may be used for making the ceramic forming device 143. For instance, the extruded body can be extruded as a core of the ceramic forming device 143. In such examples, an interior portion of the ceramic forming device 143 may be formed with the honeycomb structure 227 with the outer periphery of the ceramic forming device being built around the core honeycomb structure 227. As such, further processing of the
extruded honeycomb body itself may be avoided while the structure is incorporated as part of the ceramic forming device 143.

[0097] In further examples, the method can use a machining process to provide the ceramic forming device. For example, the machining process can be used to at least rough out the general shape of a portion of the ceramic forming device. As mentioned previously, the honeycomb structure may be used in various portions of the ceramic forming device 143 such as at least a portion of the forming wedge 211 and/or a portion of the weirs 203, 205.

[0098] The machining process, if employed, can be carried out at various alternative times during the process of making the ceramic forming device. For example, the method can carry out the machining process before firing the green body. For instance, a cutting procedure may be carried out to remove portions of the honeycomb structure 227 to obtain the desired shape characteristics. In one example, the honeycomb structure may be cut to have an outer periphery that roughly approximates, or substantially follows, an outer shape of at least a portion of the ceramic forming device 143. In just one example, the honeycomb structure may be cut to form a wedge shape approximating, such as substantially following, the outer periphery of the forming wedge 211. In addition, or alternatively, the honeycomb structure may be cut to form at least one or both of the weirs 203, 205 to approximate, such as substantially follow, the outer periphery of the weirs 203, 205.

[0099] Still further, the machining process, if employed, can machine the dried green body, after drying the green body and before firing the green body. In such examples, the machining process is carried out on the green body rather than the fired ceramic body. In addition, or alternatively, the machining process, if employed, can machine the fired ceramic body after the process of firing the green body into the ceramic body. For instance, a grinding procedure may be carried out to remove portions of the honeycomb structure 227 to obtain the desired shape characteristics. In one example, the grinding process may be used to remove portions of the honeycomb structure to have an outer periphery that roughly approximates, or substantially follows, an outer shape of at least a portion of the ceramic forming device 143. In just one example, the grinding process may machine the honeycomb structure to form a wedge shape approximating.
such as substantially following, the outer periphery of the forming wedge 211. In addition, or alternatively, the grinding process may machine the honeycomb structure to form at least one or both of the weirs 203, 205 to approximate, such as substantially follow, the outer periphery of the weirs 203, 205.

[00100] FIG. 12 schematically illustrates a process of machining that provides the honeycomb structure 227 with the peripheral shape that approximates the outer peripheral shape of the weirs 203, 205, trough 201 and forming wedge 211 of the ceramic forming device 143. As shown, a machining device 1201 such as a knife, grinding wheel, broaching device, milling device or other machining device may be used to remove outer portions of the honeycomb structure to provide the desired shape configuration. The arrangement of internal channels within the structure can also be modified to simplify or eliminate the external machining process. For example, channels can be arranged in rows running parallel to the exterior surface of the structure in both the rectangular region of the structure (toward the weirs) and the triangular wedge region of the structure. Channels in this region can also be made triangular in necessary. The transition from one channel configuration to the other moving from the rectangular region to the triangular wedge region can be abrupt or gradual over a number of channel rows.

[00101] As shown in FIG. 13, the method can further include the step of applying the outer layer 233 discussed with respect to FIG. 2 above. In one example, a refractory material can be applied and then fired to a peripheral surface of the honeycomb structure. The refractory material can be applied before firing the green body into the ceramic body. In such examples, the outer layer can be applied to the machined green body and then both can be fired together during a single firing technique. In another example, the green body can be machined and then fired into the ceramic body. Then the outer layer can be applied to the machined ceramic body and fired again to sinter the outer layer 233. In still further examples, the green body can be fired into the ceramic body. After machining the ceramic body, the outer layer 233 can be applied to the machined periphery and re-fired. As can be expected, in certain embodiments, when the honeycomb structure of the green body or the fired body is machined, the external-most surface of the machined body would comprise a plurality of partial cells. The outer layer material is then applied over the partial cell surface. The embodiment shown in FIG. 13
has the partial cells at the interface between the outer layer and the honeycomb structure substantially unfilled. Such structure may be relatively easy to make and still offers sufficient mechanical strength for the intended application. However, in certain embodiments, it is highly desired that those partial cells at the interface between the outer layer and the honeycomb inner structure be filled with the ceramic material constituting the outer layer, partly or completely. While this latter structure with the partial cells substantially completely filled (not shown in a figure) is more complex than the embodiment shown in FIG. 13, it can offer superior strength of the outer layer due to better adherence of the outer layer to the honeycomb inner structure. With the partial cells filled, the isopipe honeycomb bodies will have higher strength due to less stress concentration at the partial cells, will be less likely to have geometric deformities in the cells near the surface, will be less likely to crack at the surface / partial cell web intersection and less likely to perforate in service, which could let the glass penetrate into the cells of the honeycomb.

[00102] In just one example, after firing and machining, an alumina grog and/or alumina power and less than 25 vol.% of glasses with compositions with high viscosity can be applied to the machined surface of the ceramic honeycomb structure 227. The combination of the honeycomb structure 227 can then be reheated to 1300-1750 °C for ½ hour to 96 hours and an alumina ceramic forming device 143 with a closed porosity alumina based outer layer 233 may be obtained.

[00103] In another example, an alumina honeycomb body can be extruded and then machined into the desired shape. Before sintering, the interior of channels 231 can be filled with a low temperature melting polymer or wax. The exterior of the honeycomb structure can then be covered with a layer of alumina batch, for example, by iso-pressing. Machining can then be carried out to achieve the desired shape of the ceramic forming device 143. The polymer or wax can then be removed and then the forming device can be fired to the ceramic forming device 143.

[00104] Prophetic Example(s) and Modeling Results

[00105] Large isopipe blanks of a rectangular cross-section, of approximately 50 cm width x 100 cm height x 300 cm length are made. The blank would have a mass of 5,700 kg if the density of the isopipe material is 3.8 g/cc (assuming 95% of theoretical density,
which is 4.0 g-cm$^{-3}$). An isopipe honeycomb with an open frontal area (OFA) of 25% (i.e. 25% open channel space) would have a mass of 4,275 kg; one with 50% open frontal area would have a mass of 2,850 kg; and one with 75% open frontal area would have a mass of 1,425 kg. When the root wedge is put on the isopipe, if the wedge starts at 1/3 the height from the root, then the mass will be 4,750, 3,562.5, 2,375 and 1,187.5 kg for the 0%, 25%, 50% and 75% open frontal areas, respectively. If a root wedge is put on the isopipe where the wedge starts at 1/2 the height from the root, then the mass will be 4,275, 3,206.3, 2,137.5 and 1,068.8 kg for the 0%, 25%, 50% and 75% open frontal areas respectively. These are substantial mass savings.

Samples are extruded using a single auger (screw) extruder and large cell dies. The honeycombs are of a square cell design. The ceramic batch included the alumina particle size distribution, water level and methocel amount mentioned in previous examples. The honeycomb isopipe is extruded between 1,000 and 3,000 psi. The isopipes are sintered horizontally at a top temperature of 1550 to 1750 °C for a period of 4 to 48 hours at top temperature. The sintered web thicknesses vary from 0.5 cm to 3.0 cm and the open frontal area vary from 25% to 75%.

The cell size and cell density are shown in the below table. The combination of a 3.0 cm web thickness and a 50% open frontal area gave just under 3 cells across the isopipe and 75% open frontal area and 3.0 or 2.6 cm webs gave only -2.23 and 2.58 cells across the width of the a 50 cm isopipe. Combinations of web thickness and open frontal area that give less than 3 cells across the width of the isopipe are undesirable (underlined).

<table>
<thead>
<tr>
<th>Web Thickness (cm)</th>
<th>Cell Opening Size (cm)</th>
<th>Cell Density (cell·cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25% OFA</td>
<td>50% OFA</td>
</tr>
<tr>
<td>0.50</td>
<td>0.50</td>
<td>1.21</td>
</tr>
<tr>
<td>1.30</td>
<td>1.30</td>
<td>3.14</td>
</tr>
<tr>
<td>2.60</td>
<td>2.60</td>
<td>6.28</td>
</tr>
<tr>
<td>3.00</td>
<td>3.00</td>
<td>7.24</td>
</tr>
</tbody>
</table>

The thermal cycles for sintering large solid block monolithic refractory objects such as isopipes without through holes can take many weeks, depending upon the smallest block dimension. To illustrate one advantage of a honeycomb vs. a solid block
isopipe, let us consider firing stresses. We can use a simple slab stress model to 
illuminatethe advantage.

[00109] The stresses caused by transient thermal gradients in an infinitely long and 
ininitely high slab can be solved using a Fourier series approach. Assuming the elastic 
modulus of an extruded body is 1/10 that of a fully dense body and the thermal diffusivity 
is also 1/10 that of a fully dense body, one can make an estimate of the relative firing 
times / heating rates for various thicknesses for slabs. It can be inferred that the cell wall 
thickness and the smallest monolithic isopipe dimension will be the controlling 
thicknesses. The elastic modulus is ~ 55 x 10^6 psi and the thermal diffusivity is about 12 
x 10^-6 m^2/sec for a dense alumina. One can approximate a powder body by dividing these 
values by 10 (when comparing thicknesses of the same extruded powder, the ratio of the 
heating rates for a given stress level is actually independent of the particular e-modulus 
and thermal diffusivity as they are the same in both calculations and one is looking for a 
ratio).

[00110] Raleigh’s equation can be written with a Fourier series as:

\[
\sigma(\chi) = 4a \frac{E(R-T)}{\pi(1-v)} \sum_{n=1}^{12} \left[ \frac{1}{(2n-1)} e^{\frac{-k \chi \left( (2n-1)^2 \cdot \frac{1}{h^2} \right)}{\pi^2}} - \frac{2}{\pi (2n-1)} (-1)^n + 1 \cos \left( (2n-1) \frac{\pi \chi}{2h} \right) \right]
\]

where \( \sigma \) is the stress, \( a \) is the thermal expansion coefficient, \( \chi \) is the location in the slab, \( E \) 
is the elastic modulus, \( R-T \) is the step change in temperature for the model (1° C in this 
calculation), \( v \) is Poisson's ratio, \( k \) is thermal diffusivity, \( t \) is time and \( h \) is half the slab 
thickness.

[00111] As the diffusion equations have all the same constants, and the only variables 
are time and thickness, the same stress with the same temperature differential is reached 
in 1/100 the time in a body that is 1/10 the thickness.

[00112] In addition to low temperature heating rate/diffusivity considerations, at 
elevated temperature the sintering cycle can be controlled by sintering shrinkage rate and 
other factors, and the diffusivity analysis does not apply. However, conservatively, one 
can reduce the firing time in the slow heat up, diffusion controlled region by over a factor 
of 5-10 when one makes a 5 cm web honeycomb or thinner web honeycomb isopipe 
rather than a solid monolithic block isopipe of 50 cm thickness. Thus, we can sinter a 50 
cm width x 100 cm height x 3000 mm length honeycomb isopipe blank according to the
present disclosure within one week, as compared to many weeks required for a solid body.

[00113] 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 ceramic forming device for fusion drawing a glass ribbon comprising:
   a forming wedge comprising a pair of downwardly inclined forming surface portions extending between opposed ends of the forming wedge, the pair of downwardly inclined forming surface portions each converging along a downstream direction to form a root of the forming wedge, wherein a honeycomb structure forms at least a portion of the ceramic forming device with the honeycomb structure comprising a plurality of walls at least partially defining a plurality of channels.

2. The ceramic forming device of claim 1, further comprising a trough at least partially defined by a pair of weirs including a first weir and a second weir defining opposite sides of the trough.

3. The ceramic forming device of claim 2, wherein the trough includes a depth between a top of at least one of the pair of weirs and a lower portion of the trough that varies along an axis of the ceramic forming device.

4. The ceramic forming device of claim 2, wherein the honeycomb structure forms at least a portion of the pair of weirs.

5. The ceramic forming device of claim 4, wherein the honeycomb structure forms at least a portion of the forming wedge.

6. The ceramic forming device of claim 1, wherein the honeycomb structure forms at least a portion of the forming wedge.

7. The ceramic forming device of claim 1, wherein each of the plurality of walls of the honeycomb structure includes a thickness defined between a corresponding pair of channels from about 0.5 mm to about 30 mm.

8. The ceramic forming device of claim 1, wherein the honeycomb structure has a channel density of about 1/25 channel/cm² to about 20 channels/cm².

9. The ceramic forming device of claim 1, further comprising an outer layer of refractory material positioned over a peripheral surface of the honeycomb structure.

10. The ceramic forming device of claim 9, wherein the outer layer of refractory material comprises a ceramic material.
11. The ceramic forming device of claim 10, wherein the ceramic material of the outer layer comprises a closed-cell porous structure.

12. A method of fusion drawing a glass ribbon comprising the steps of:
   (I) providing a ceramic forming device comprising a trough at least partially defined by a pair of weirs including a first weir and a second weir defining opposite sides of the trough, the ceramic forming device further including a forming wedge comprising a pair of downwardly inclined forming surface portions extending between opposed ends of the forming wedge, the pair of downwardly inclined forming surface portions each converging along a downstream direction to form a root of the forming wedge, wherein a honeycomb structure forms at least a portion of the ceramic forming device with the honeycomb structure comprising a plurality of walls at least partially defining a plurality of channels;
   (II) introducing glass melt into the trough of the ceramic forming device;
   (III) spilling the molten glass from the trough over top edges of the pair of weirs such that corresponding molten glass sheets travel down the respective inwardly inclined forming surface portions; and
   (IV) fusion drawing the molten glass sheets together as a glass ribbon off the root of the forming wedge.

13. The method of claim 12, wherein step (I) provides the honeycomb structure forming at least a portion of the pair of weirs.

14. The method of claim 12, wherein step (I) provides the honeycomb structure forming at least a portion of the forming wedge.

15. The method of claim 12, wherein step (I) provides the honeycomb structure forming substantially the entire forming wedge.

16. The method of claim 15, wherein step (I) provides an outer layer of refractory material positioned over a peripheral surface of the honeycomb structure forming the forming wedge.

17. The method of claim 12, wherein step (I) provides an outer layer of refractory material positioned over a peripheral surface of the honeycomb structure.
18. The method of claim 12, wherein step (I) provides each of the plurality of walls of the honeycomb structure with a thickness defined between a corresponding pair of channels from about 0.5 mm to about 30 mm.

19. The method of claim 12, wherein step (I) provides the honeycomb structure with a channel density of about 1/25 channel/cm² to about 20 channels/cm².

20. A method of making a ceramic forming device for fusion drawing a glass ribbon comprising the steps of:

   (I) extruding a ceramic-forming batch material through a die member to form a green body with a honeycomb structure including a plurality of walls at least partially defining a plurality of channels extending through the green body, wherein each of the plurality of walls has a thickness defined between a corresponding pair of the channels from about 0.5 mm to about 30 mm;

   (II) firing the green body to form a fired ceramic body with the honeycomb structure; and

   (III) providing the ceramic forming device with a wedge and a trough at least partially defined by a pair of weirs, wherein the honeycomb structure forms at least a portion of the ceramic forming device.

21. The method of claim 20, wherein step (III) includes using a machining process to provide the ceramic forming device.

22. The method of claim 21, wherein machining process of step (III) includes machining the green body before step (II).

23. The method of claim 21, wherein the machining process of step (III) includes machining the fired ceramic body after step (II).

24. The method of claim 20, wherein step (I) forms the honeycomb structure with a channel density of about 1/25 channel/cm² to about 20 channels/cm².

25. The method of claim 20, wherein the honeycomb structure forms at least a portion of the wedge of the ceramic forming device.

26. The method of claim 20, wherein the ceramic body includes a substantially closed-cell porous structure.

27. The method of claim 20, further comprising the step of preparing the ceramic-forming material by mixing a first quantity of particles having a first mean particle size
with a second quantity of particles having a second mean particle size greater than the first mean particle size.

28. The method of claim 27, wherein the first and second quantity of particles comprise alumina particles.

29. The method of claim 28, wherein the first mean particle size of the first quantity of alumina particles is about 0.6 microns and the second mean particle size of the second quantity of alumina particles is about 2.7 microns.

30. The method of claim 28, wherein the weight ratio of the first quantity of alumina particles to the second quantity of alumina particles is about 3:1.

31. The method of claim 27, wherein the first and second quantity of particles comprise zircon particles.

32. The method of claim 31, wherein the first mean particle size of the first quantity of zircon particles is about 1 micron and the second mean particle size of the second quantity of zircon particles is about 7 microns.

33. The method of claim 31, wherein the weight ratio of the first quantity of zircon particles to the second quantity of zircon particles is about 1:1.

34. The method of claim 20, further comprising the step of applying an outer layer of refractory material to a peripheral surface of the honeycomb structure.

35. The method of claim 20, further comprising the step of reducing an oxygen level of an atmosphere in a firing chamber during step (II).

36. The method of claim 20, further comprising the step of forcing fluid through the plurality of channels during step (II).

37. The method of claim 20, further comprising the step of forcing steam through the plurality of channels during step (II).

38. A method of making a ceramic forming device for fusion drawing a glass ribbon comprising the steps of:
   (I) extruding a ceramic-forming batch material through a die member to form a green body with a honeycomb structure including a plurality of walls at least partially defining a plurality of channels extending through the green body, wherein each of the plurality of walls has a thickness defined between a corresponding pair of the channels
from about 0.5 mm to about 30 mm and the honeycomb structure includes a channel density of about 1/25 channel/cm² to about 20 channels/cm²;

(II) machining the green body such that a green forming device is provided with a wedge and a trough at least partially defined by a pair of weirs, wherein the honeycomb structure forms at least a portion of the green forming device; and

(III) firing the green forming device to form a fired ceramic forming device with the honeycomb structure.

39. A method of making a ceramic forming device for fusion drawing a glass ribbon comprising the steps of:

(I) extruding a ceramic-forming batch material through a die member to form a green body with a honeycomb structure including a plurality of walls at least partially defining a plurality of channels extending through the green body, wherein each of the plurality of walls has a thickness defined between a corresponding pair of the channels from about 0.5 mm to about 30 mm and the honeycomb structure includes a channel density of about 1/25 channel/cm² to about 20 channels/cm²;

(II) firing the green body to form a fired ceramic body with the honeycomb structure; and

(III) machining the fired ceramic body such that the ceramic forming device is provided with a wedge and a trough at least partially defined by a pair of weirs, wherein the honeycomb structure forms at least a portion of the ceramic forming device.
# INTERNATIONAL SEARCH REPORT

**International application No:**
PCT/US2012/052208

**A. CLASSIFICATION OF SUBJECT MATTER**

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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

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**

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Further documents are listed in the continuation of Box C. See patent family annexe.

Special categories of cited documents:

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- "Z" document member of the same patent family

Date of the actual completion of the international search: 19 November 2012

Date of mailing of the international search report: 05/12/2012

Name and mailing address of the ISA/Authorized officer:

European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk
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Fax: (+31-70) 340-3016

Martinek, K
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