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— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

(54) **Title:** SYSTEMS AND METHODS FOR REDUCING RATE OF CURL IN DC CASTING

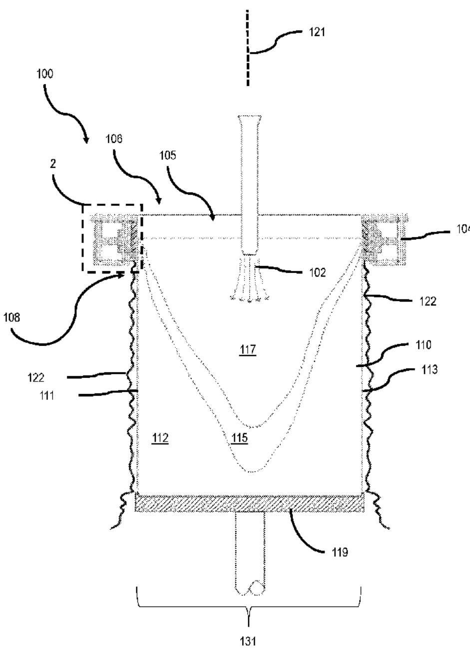

FIG. 1

(57) **Abstract:** A direct chill casting system includes a mold for forming an ingot. The mold defines an open-ended casting cavity having a casting axis and includes a plurality of discharge channels for discharging coolant the ingot. The plurality of discharge channels include first discharge channels which receive the coolant at a first flow rate and second discharge channels which receive the coolant at a second flow rate which is different from the first flow rate. Controllers may be at least partially within the first discharge channels or the second discharge channels for controlling the flow rates.

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SYSTEMS AND METHODS FOR REDUCING RATE OF CURL IN DC CASTING

REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of and priority to U.S. Provisional Patent Application No. 63/617,890, filed on January 5, 2024, and entitled SYSTEMS AND METHODS FOR REDUCING RATE OF CURL IN DC CASTING, the content of which is hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

[0002] This application relates to the casting of metals such as but not limited to aluminum and aluminum alloys, and more particularly to systems and methods for reducing a rate of curl during the casting of an ingot.

BACKGROUND

[0003] In direct chill casting, molten metal is passed into a mold cavity with a false, or moving, bottom. As the molten metal enters the mold cavity, generally from the top, the false bottom lowers at a rate related to the rate of flow of the molten metal. The molten metal that has solidified near the sides can be used to retain the liquid and partially liquid metal in the metal sump. The metal can be 99.9% solid (e.g., fully solid), 100% liquid, and anywhere in between. The metal article resulting from the direct chill casting process can be referred to as an ingot. An ingot may have a generally rectangular cross section, although other cross sections may be used, such as circular or even non-symmetric. A “butt” of the ingot refers to the portion of the ingot formed during the start of casting, and the “head” of the ingot refers to the portion of the ingot formed at the end of casting. The term ingot, as used herein, can be inclusive of any direct chill cast metal article, including billets, as appropriate.

[0004] Butt curl is a known and undesired phenomena incurred during the casting of some metals and/or shapes, and is generally caused by the shrinking of some portions of the ingot relative to other portions. Excessive butt curl may result in bleed-out situations in which molten metal escapes during the casting process and requires that casting be aborted. A (rapid?) rate of butt curl causes the formation of a notch in the butt of the ingot. Traditional approaches of uniformly discharging coolant on the ingot result in a rapid rate of butt curl, and therefore notches formed in the ingot are relatively severe or abrupt.

[0005] After casting, ingots may be processed by rolling mills to reduce the thickness of the ingot and produce metal products into a more usable form for further processing, such as a coil of a rolled aluminum sheet. As the ingots are reduced in the rolling mill, cracks may form in the edges and grow in size with subsequent passes through the rolling mill. Such cracks commonly form in the butt of the ingot, and in particular are caused by the notch in the ingot. The cracks are undesirable and must be removed via shear cutting, edge trimming, and other similar processes, thereby producing material waste and affecting processing efficiency of such ingots. Edge cracks that are too deep may remain within the sheet and may not be observed until after the sheet is coiled, thereby requiring unwrapping of the coil to access and address the edge cracks.

SUMMARY

[0006] Embodiments covered by this patent are defined by the claims below, not this summary. This summary is a high-level overview of various embodiments and introduces some of the concepts that are further described in the Detailed Description section below. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this patent, any or all drawings, and each claim.

[0007] According to certain embodiments, a direct chill casting system includes a mold for forming an ingot. The mold defines an open-ended casting cavity with a casting axis and further includes a plurality of discharge channels to discharge coolant onto the ingot. Each discharge channel includes an input aperture for receiving the coolant and a discharge aperture for discharging the coolant. In various embodiments, a first discharge channel of the plurality of discharge channels receives the coolant at a first flow rate and a second discharge channel of the plurality of discharge channels receives the coolant at a second flow rate different from the first flow rate.

[0008] According to various embodiments, a direct chill casting system includes a mold for forming an ingot. The mold defines an open-ended casting cavity having a casting axis and includes a plurality of discharge channels to discharge coolant onto the ingot. A controller may be positioned at least partially within a first discharge channel of the plurality of discharge channels such that a flow rate of coolant discharged by the first discharge channel is different from a flow rate of coolant from a second discharge channel of the plurality of discharge channels.

[0009] According to some embodiments, a direct chill casting system includes a mold for forming an ingot. The mold defines an open-ended casting cavity having a casting axis and includes a plurality of discharge channels to discharge coolant onto a rolling face of the ingot. The plurality of discharge channels include first discharge channels which receive the coolant at a first flow rate and second discharge channels which receive the coolant at a second flow rate different from the first flow rate.

[0010] According to certain embodiments, a direct chill casting system includes a mold for forming an ingot having opposing rolling faces. The mold defines an open-ended casting cavity having a casting axis and includes a plurality of discharge channels to discharge coolant onto a first rolling face of the opposing rolling faces of the ingot. In certain embodiments, the plurality of discharge channels includes first discharge channels and second discharge channels, and a flow rate of coolant through the first discharge channels is adjustable and such that the flow rate of coolant from the first discharge channels is different from the flow rate of coolant from the second discharge channels.

[0011] According to various embodiments, a method of casting an ingot includes receiving molten metal in the casting cavity defined by a mold and causing a bottom block to move away from a lower end of the mold. The method includes discharging coolant from the plurality of discharge channels of the mold at varying flow rates onto a rolling face of the ingot emerging from the mold as the bottom block moves away from the lower end of the mold by varying the flow rate of coolant received by the plurality of discharge channels.

[0012] According to various embodiments, a direct chill casting system includes a mold for forming an ingot. The mold defines an open-ended casting cavity with a casting axis and further includes at least one discharge channel configured to discharge coolant onto the ingot. In various embodiments, the discharge channel includes a plurality of input apertures for receiving the coolant and a plurality of discharge apertures for discharging the coolant, and the plurality of input apertures are fluidly connected to the plurality of discharge apertures. In some embodiments, a first input aperture of the plurality of input apertures may receive the coolant at a first flow rate, and a second input aperture of the plurality of input apertures may receive the coolant at a second flow rate different from the first flow rate.

[0013] According to some embodiments, a direct chill casting system includes a mold for forming an ingot, where the mold defines an open-ended casting cavity having a casting axis and includes at least one discharge channel configured to discharge coolant onto the ingot. In various embodiments, the at least one discharge channel includes a plurality of input apertures and of discharge apertures fluidly connected to the plurality of input apertures. In some embodiments, a controller may be at least partially within at least one input aperture of the plurality of input apertures of the at least one of discharge channel such that a flow rate of coolant discharged by the at least one input aperture is different from a flow rate of coolant from another input aperture of the at least one discharge channel.

[0014] According to certain embodiments, a direct chill casting system includes a mold for forming an ingot. The mold defines an open-ended casting cavity having a casting axis and the mold comprises at least one discharge channel configured to discharge coolant onto a rolling face of the ingot. In some embodiments, the at least one discharge channel includes first input apertures configured to receive the coolant at a first flow rate and second input apertures configured to receive the coolant at a second flow rate which is different from the first flow rate.

[0015] Various implementations described herein can include additional systems, methods, features, and advantages, which cannot necessarily be expressly disclosed herein but will be apparent to one of ordinary skill in the art upon examination of the following detailed description and accompanying drawings. It is intended that all such systems, methods, features, and advantages be included within the present disclosure and protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The specification makes reference to the following appended figures, in which use of like reference numerals in different figures is intended to illustrate like or analogous components.

[0017] FIG. 1 illustrates a metal casting system according to embodiments.

[0018] FIG. 2 is a sectional view of a portion of the metal casting system of FIG. 1 taken from box 2 in FIG. 1.

[0019] FIG. 3 is a schematic top view of a portion of the metal casting system of FIG. 1.

[0020] FIG. 4 is a sectional view of a portion of a metal casting system according to embodiments.

[0021] FIG. 5 is a schematic top view of a portion of the metal casting system of FIG. 4.

[0022] FIG. 6 is a schematic top view of a portion of a metal casting system according to embodiments.

[0023] FIGS. 7A-B illustrate notches in ingots.

DETAILED DESCRIPTION

[0024] Described herein are systems and methods for reducing and/or controlling rate of butt curl formation in ingots during casting. In certain embodiments, reducing and/or controlling the rate of butt curl formation may reduce a severity of a notch formed in the ingot, thereby reducing edge cracking traditionally caused by the notch in the ingot. In various embodiments, reducing the severity of the notch using the systems and methods described herein may reduce initiation points of a crack and/or may reduce liquation in the area of the notch. In some embodiments reducing the rate of curl may reduce bleed-outs from the curl, thereby increasing safety (e.g., bleed-outs can cause explosions) and improving processing performance (e.g., bleed-outs lead to lost casting time).

[0025] In certain embodiments, the systems and methods described herein reduce the rate of butt curl by providing variable flow of coolant across a surface of an ingot, such as but not limited to a rolling face of the ingot. Modifying the flow of coolant across the surface of the ingot may smooth out and/or reduce the severity of the notch formed in the ingot. While the following description makes reference to providing variable flow of coolant across a rolling face of the ingot as the surface of the ingot, in other embodiments, the systems and methods described herein may be utilized on any section of a mold and/or any surface of an into. Modifying the flow of coolant may further make the casting process more robust and consistent while reducing edge cracking.

[0026] In some embodiments, the systems and methods described herein may discharge coolant from dispensing channels in a mold of the casting system. The dispensing channels generally include an input aperture (also known as a “baffle hole”) for receiving a flow of coolant and a discharge aperture (also known as a “jet hole”) for discharging the coolant onto the ingot. The systems and methods described herein may provide variable flow of coolant onto the ingot by controlling the flow rate of coolant at and/or through the input aperture. In some embodiments, controlling the flow rate at the input aperture may include permanently changing a size (e.g., transverse dimension) of the input aperture and/or utilizing one or more controllers at least partially within the input aperture. Non-limiting examples of controllers may include wires, inserts, hollow sleeves, and/or other devices suitable for controlling the flow rate through the input aperture. In certain embodiments, controlling the flow rate at the input aperture may provide an improved and/or increased impact on the flow of coolant as the input apertures are typically smaller than the discharge apertures.

[0027] The cooling provided by the systems and methods described herein may provide various cooling and/or heat transfer profiles across a rolling face of the ingot. In some embodiments, the systems and methods described herein may provide non-uniform cooling and/or heat transfer profiles across the rolling face of the ingot. In one non-limiting example, the systems and methods described herein provide a heat transfer profile with less heat transfer at a center portion of the rolling face compared to edge portions (e.g., resulting in a higher temperature at the center portion of the rolling face), which may reduce a rate of butt curl. Other profiles may be realized using the systems and methods described herein.

[0028] Various other benefits and advantages may be realized with the systems and methods described herein, and the aforementioned benefits and advantages should not be considered limiting.

[0029] FIGS. 1-3 illustrate an example of a direct chill (DC) casting system 100 for casting an ingot 110 according to various embodiments. The ingot 110 cast by the DC casting system 100 may be various metals as desired, including but not limited to aluminum, aluminum alloys, steel, or other metals as desired. In some examples, the ingot 110 may be aluminum or an aluminum alloy in the 1xxx series, 2xxx series, 3xxx series, 4xxx series, 5xxx series, 6xxx series, 7xxx series, 8xxx series and/or any other aluminum or aluminum alloy.

[0030] The DC casting system 100 generally includes an open-ended mold 104. Molten metal 102 may be introduced into a mold cavity 105 of the mold 104 through a mold inlet 106 and emerge as the ingot 110 from a mold outlet 108. The ingot 110 emerging from the mold outlet 108 generally includes opposing rolling faces 111, 113 (i.e., faces defining a width of the ingot 110), and a distance 131 between the faces 111, 113 is generally a thickness of the ingot 110.

[0031] The ingot 110 being cast can include metal in various stages of solidification including solidified metal 112, transitional metal 115, and molten metal 117. In particular, the upper part of the ingot 110 may have the molten metal 117 that forms an inwardly tapering sump within the region of solidified metal 112 of the ingot 110. As the distance from the mold outlet 108 increases (via a movable bottom block 119), the core of the ingot cools, and the region of solidified metal 112 of the ingot continues to thicken until a completely solid cast ingot 110 is formed at a certain distance below the mold outlet 108.

[0032] The mold 104 may be various types of molds as desired. In certain embodiments, and as discussed in greater detail below with reference to FIGS. 2 and 3, the mold 104, which may be internally cooled with a coolant such that the mold 104 has cooled casting surfaces, provides initial primary cooling of the molten metal and peripherally confines and cools the molten metal to start formation of the region of solidified metal 112 of the ingot 110. The cooling metal moves out and away from the mold 104 through the mold outlet 108 along a casting axis 121. As illustrated in FIG. 1, coolant 122 is directed from the mold 104 onto the outer surface of the ingot 110 as it emerges from the mold 104 in order to provide secondary cooling that thickens the region of solidified metal 112 and enhances the cooling process. The coolant may be a liquid, including but not limited to water.

[0033] Referring to FIGS. 2 and 3, the mold 104 generally includes a body 114. Optionally, and depending on the type of mold 104, the mold 104 may include a casting surface member 123 supported on the body 114. The casting surface member 123 forms a casting surface 125 of the mold 104 and may be various materials as desired, such as but not limited to graphite or other casting surface material. The casting surface member 123 may be supported on the body 114 using various techniques as desired, such as but not limited to adhesives, mechanical means, and/or as otherwise desired. In other embodiments, the casting surface member 123 is omitted, and other mold technologies may be utilized as the mold 104.

[0034] The body 114 of the mold 104 defines one or more coolant chambers 116 for coolant. In the embodiment illustrated, the body 114 includes two coolant chambers 116A-B, although the number of coolant chambers 116 should not be considered limiting, and in other embodiments, fewer or additional coolant chambers 116 may be utilized. Along a perimeter of the mold 104, the chambers 116 may be continuous and/or may be subdivided into sections as desired. Optionally, a top cover 118 and/or a bottom cover 120 may be removable from and/or attachable to the body 114 and to provide selective access to the coolant chambers 116. When the covers 118, 120 are included, one or more sealing members 127 may be utilized to seal the coolant chambers 116.

[0035] In addition to the one or more coolant chambers 116, the body 114 of the mold 104 includes one or more discharge channels 124 for receiving coolant from the one or more coolant chambers 116 and discharging the coolant 122 onto the ingot 110. Each discharge channel 124 includes one or more baffle or input apertures 126 and one or more jet or discharge aperture 128. As a non-limiting example, in some embodiments, a discharge channel 124 may include a single input aperture 126 and a single discharge aperture 128. As additional non-limiting examples, in certain embodiments, a discharge channel 124 may include a plurality of input apertures 126 fluidly connected to a single discharge aperture 128, a plurality of input apertures 126 fluidly connected to a plurality of discharge apertures 128 and/or a single input aperture 126 fluidly connected to a plurality of discharge apertures 128. As such, the particular arrangement of the one or more discharge channels 124 illustrated should not be considered limiting.

[0036] In some embodiments, the input aperture 126 may have a transverse dimension (e.g., diameter) less than that of the discharge aperture 128, although it need not in other embodiments. The input aperture 126 receives a flow of coolant from the corresponding coolant chamber 116, and coolant flows through the discharge channel 124 from the input aperture 126 to the discharge aperture 128. The coolant is thereby discharged from the discharge aperture 128 of the discharge channel 124 toward the ingot 110. In some embodiments, and as illustrated in FIG. 3, a chamber or groove portion 129 may connect a plurality of input apertures 126 and a plurality of discharge apertures 128. In the example illustrated, the input apertures 126 may be offset relative to the discharge apertures 128. In such embodiments with the groove portion 129 connecting a plurality of input apertures 126 and/or a plurality of discharge apertures 128, controlling the flow rates of coolant received by any input aperture 126 (discussed in detail below) may affect the flow of coolant from one or more discharge apertures.

[0037] Various configurations of discharge channels 124 and/or molds may be utilized, and the particular configuration of discharge channels 124 illustrated should not be considered limiting.

As such, the particular arrangement of the mold 104, the body 114, the coolant chambers 116, and discharge channels 124 should not be considered limiting. As a non-limiting example, compared to the mold 104, another suitable mold may include a single coolant chamber, such as but not limited to a configuration of a water hole mold. In this example, a baffle plate may be provided within a chamber defined by the body of the mold, thereby sub-dividing the chamber into a main chamber and a baffle chamber (defined between the mold body and baffle plate). Input apertures may be defined in the baffle plate, and the baffle chamber may fluidly connect the input apertures with a plurality of discharge apertures. In this example, the baffle chamber connects a plurality of input apertures and/or a plurality of discharge apertures, and similar to the mold 104, controlling the flow rates of coolant received by any input aperture may affect the flow of coolant from one or more discharge apertures. In another non-limiting example, a mold may have two chambers similar to the mold 104, and each input aperture 126 is inline with and connected to a particular discharge channel 128, and a connecting groove portion 129 may be omitted. In this example, compared to the mold 104, controlling the flow rate of coolant received by an input aperture will only affect the flow of coolant from one discharge apertures 128 (e.g., the corresponding discharge aperture). See, e.g., FIG. 5.

[0038] In certain embodiments, the discharge channels 124 are controlled such that, across a rolling face of the ingot 110 (e.g., rolling face 111 and/or rolling face 113), the mold 104 discharges a varying and/or non-uniform flow of coolant. Varying the flow of coolant across the rolling face thereby varies the heat transfer occurring at different portions of the rolling face. In one non-limiting example, the discharge channels 124 are controlled to decrease cooling in a center portion of a rolling face relative to side portions of the rolling face (i.e., the center of the rolling face may have a higher temperature relative to side portions of the rolling face). However, in other embodiments, various cooling and/or heat transfer profiles may be realized by varying the flow of coolant.

[0039] In various embodiments, the discharge channels 124 are controlled to provide varying and/or non-uniform flow of coolant by controlling a flow rate of coolant received by the discharge channels 124 in the input apertures 126. Accordingly, in certain embodiments, across one of the rolling faces of the ingot 110, one or more discharge channels 124 may receive the coolant at a first flow rate and one or more discharge channels 124 may receive coolant at a second flow rate different from the first flow rate. Moreover, while two received flow rates of coolant are discussed, in other embodiments, any number of different flow rates may be provided to the discharge channels 124. Non-limiting examples of systems and methods for varying the flow rates received by the discharge channels 124 are described in detail below, but the below examples should not be considered limiting. The systems and methods for varying the flow rates of coolant received by the discharge channels 124 may be permanently provided with the mold 104 (e.g., fixed and/or unchanging), and/or may be adjustable as desired. In one non-limiting example and as discussed in detail below, the flow rate of coolant received by one or more discharge channels 124 may be automatically adjustable (e.g., using actuators and/or other techniques or mechanisms as desired). In some embodiments, varying the flow rate of coolant received by the discharge channels 124 may include at least partially obstructing one or more input apertures 126 that are of uniform size (see, e.g., FIGS. 2-5), modifying the size of the input apertures 126 (see, e.g., FIG. 6), and/or combinations thereof. While the below examples are discussed in the context of two different flow rates (or zones of flow on the mold 104), the mold 104 may include a plurality of zones of different flow, such as two zones, three zones, four zones, five zones, six zones, seven zones, eight zones, nine zones, ten zones, and/or more than ten zones of different flow as desired. The plurality of zones of flow may be achieved by varying the presence of a controller 130 (discussed below), a characteristic of the controller 130, sizes of the input apertures 126, geometries of the input apertures 126, and/or as otherwise desired.

[0040] In some embodiments, the flow rate of coolant received by one or more discharge channels 124 is controlled by one or more controllers 130 positioned at least partially within an input aperture 126. The controllers 130 may be various devices or mechanisms as desired suitable for occluding the input aperture 126, such as but not limited to inserts, sleeves, plugs, wires, pins, combinations thereof, and/or other suitable devices as desired. In embodiments with a plurality of controllers 130, the controllers 130 may be a same type of controller (e.g., all inserts) and/or the controllers 130 may be various combinations of controllers. Moreover, for a given type of controller 130, a characteristic of the controller 130 may be varied to provide a plurality of zones of flow on the mold 104. As non-limiting examples, wiring may be provided as the controllers 130, but the wires may be provided in three different gauges or sizes to provide at least three different flow rates.

[0041] In the embodiment of FIGS. 2 and 3, the controllers 130 are wires 136 positioned at least partially within one or more input apertures 126. Referring to FIG. 3, by positioning the wires 136 as controllers 130 within some of the input apertures 126, the mold 104 may include one or more first input apertures 126A which receive coolant at a first flow rate and one or more second input apertures 126B which receive coolant at a second flow rate different from the first flow rate. The number, pattern, and/or arrangement of controllers 130 thereby defining the first input apertures 126A and input apertures 126B is for illustrative purposes and should not be considered limiting.

[0042] In some embodiments, the wires 136 as controllers 130 may have a same diameter and/or different diameters as desired. As a non-limiting example, some wires 136 may have a first diameter for providing a first amount of obstruction of the input aperture 126 while other wires 136 may have a second diameter providing a second (or different) amount of obstruction of the input aperture 126. The mold 104 with wires 136 having different diameters may provide further varying and/or non-uniform flow of coolant as desired.

[0043] In some embodiments, the wires 136 as controllers 130 may be permanently positioned at least partially within the corresponding input apertures 126. In other embodiments, the wires 136 may be removably supported using various techniques as desired such that the wires 136 may be positioned within and removed from a particular input aperture 126 as desired. Removable wires 136 may allow for the mold 104 to be modified as desired to provide a desired flow of coolant, thereby providing improved performance and modularity to the system 100 to perform various casting processes without requiring the expense of a new mold 104. In embodiments where the wires 136 are removable, the wires 136 optionally may be automatically removable and/or positionable relative to the input apertures 126. As a non-limiting example, an actuator may be coupled to one or more wires 136 to automatically position the wire 136 within the input aperture 126, remove the wire 136 from the input aperture 126, and/or to change the wire 136 (e.g., change from a wire with a smaller diameter to a wire with a large diameter).

[0044] FIGS. 4 and 5 illustrate a DC casting system 400 that is substantially similar to the DC casting system 100 except that the mold 104 includes hollow sleeves 432 as the controllers 130 to vary the flow rates that the discharge channels 124 receive the coolant in the input apertures 126. In addition, compared to the DC casting system 100, a discharge channel 124 includes an input aperture 126 with a corresponding discharge aperture 128, and an optional connecting portion 429 connects the corresponding input apertures 126 and discharge aperture 128. In other embodiments, the connecting portion 429 may be omitted. In this example, the sleeves 432 may be at least partially positioned within one or more of the input apertures 126, and the coolant flows through inner passages 434 of the sleeves 432, thereby controlling the flow rate of coolant into the discharge channels 124. Similar to the wires 136 as controllers 130, the number, pattern, and arrangement of sleeves 432 should not be considered limiting. Moreover, while in some embodiments the sleeves 432 may be the same, in other embodiments, they need not. As a non-limiting example, the inner passage 434 of one sleeve 432 may have a diameter less than that of another sleeve 432. Similar to the wires 136, the sleeves 432 may be fixed relative to the mold 104 and/or may be removable from the mold 104 as desired. Optionally, the sleeves 432 may be automatically positionable relative to the input apertures 126 using one or more actuators.

[0045] In another embodiment, the sleeves 432 need not be hollow, and instead the sleeves 432 may be plugs positioned within one or more input apertures 126. In this embodiment, the sleeves 432 as plugs may fully plug or restrict flow through the input apertures 126 in which they are positioned. The plugging of the input apertures 126 may be arranged on the mold 104 to provide variable flow in the discharge apertures 128

[0046] FIG. 6 illustrates another example of DC casting system 600 that is similar to the DC casting system 100. Compared to the DC casting system 100 in which uniformly-sized input apertures 126 were controlled with one or more controllers 130, in the DC casting system 600, the input apertures 126 have a non-uniform size across the rolling face of the ingot 110. In this example, the mold 104 includes one or more first input apertures 126A with a first transverse dimension to receive coolant at a first flow rate and one or more second input apertures 126B having a second transverse dimension (that is different from the first transverse dimension) to receive coolant at a second flow rate different from the first flow rate. Additional discharge channels 124 having input apertures 126 with different transverse dimensions may be utilized as desired, and the number, pattern, and/or size of the input apertures 126 illustrated in FIG. 6 should not be considered limiting.

[0047] In certain embodiments, one or more controllers 130 may be utilized with the mold 104 having non-uniform input apertures 126. As a non-limiting example, the wires 136 and/or the sleeves 432 as controllers 130 may be positioned at least partially within one or more of the non-uniform input apertures 126 to further vary the flow rate of coolant received by the discharge channels 124.

[0048] FIG. 7A illustrates an ingot 710A formed using the systems and methods described herein with variable flow of coolant across the ingot, and FIG. 7B illustrates an ingot 710B formed using traditional approaches with uniform application of coolant. As illustrated in FIG. 7A, a notch 751A formed in the ingot 710A is relatively reduced or gradual, while a notch 751B formed in the ingot 710B is relatively severe and abrupt. During rolling, the severe notch 751B is more susceptible to edge cracking.

[0049] A collection of exemplary embodiments is provided below, including at least some explicitly enumerated as an "Illustration" providing additional description of a variety of example embodiments in accordance with the concepts described herein. These illustrations are not meant to be mutually exclusive, exhaustive, or restrictive; and the disclosure not limited to these example illustrations but rather encompasses all possible modifications and variations within the scope of the issued claims and their equivalents.

[0050] Illustration 1. A direct chill casting system comprising a mold for forming an ingot, wherein the mold defines an open-ended casting cavity with a casting axis and further comprises a plurality of discharge channels configured to discharge coolant onto the ingot, wherein: each discharge channel comprises an input aperture for receiving the coolant and a discharge aperture for discharging the coolant; a first discharge channel of the plurality of discharge channels is configured to receive the coolant at a first flow rate; and a second discharge channel of the plurality of discharge channels is configured to receive the coolant at a second flow rate different from the first flow rate.

[0051] Illustration 2. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, further comprising a controller at least partially within the input aperture of the first discharge channel and such that the coolant is received in the first discharge channel at the first flow rate.

[0052] Illustration 3. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the controller comprises at least one of a sleeve, a wire, or an insert.

[0053] Illustration 4. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the controller is a first controller, and wherein the direct chill casting system further comprises a second controller at least partially within the input aperture of the second discharge channel and such that the coolant is received in the second discharge channel at the second flow rate.

[0054] Illustration 5. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the plurality of discharge channels comprises a plurality of first discharge channels and a plurality of second discharge channels, wherein the plurality of first discharge channels are configured to discharge coolant on a first portion of a rolling face of the ingot, and wherein the plurality of second discharge channels are configured to discharge coolant on a second portion of the rolling face of the ingot.

[0055] Illustration 6. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the first discharge channels and the second discharge channels are arranged in the mold such that the flow rate of coolant discharged across a rolling face of the ingot is non-uniform.

[0056] Illustration 7. A direct chill casting system comprising: a mold for forming an ingot, wherein the mold defines an open-ended casting cavity having a casting axis and comprises a plurality of discharge channels configured to discharge coolant onto the ingot; and a controller at least partially within a first discharge channel of the plurality of discharge channels such that a flow rate of coolant discharged by the first discharge channel is different from a flow rate of coolant from a second discharge channel of the plurality of discharge channels.

[0057] Illustration 8. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the controller comprises at least one of a sleeve, a wire, or an insert.

[0058] Illustration 9. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the controller is removable from the first discharge channel.

[0059] Illustration 10. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the controller is at least partially within the first discharge channel such that the flow rate of coolant received by the first discharge channel is less than the flow rate of coolant received by the second discharge channel.

[0060] Illustration 11. The direct chill casting system of claim 7, wherein the controller is a first controller of a plurality of controllers, wherein each controller of the plurality of controllers is positioned at least partially within a corresponding discharge channel of the plurality of discharge channels.

[0061] Illustration 12. A direct chill casting system comprising: a mold for forming an ingot, wherein the mold defines an open-ended casting cavity having a casting axis and comprises a plurality of discharge channels configured to discharge coolant onto a rolling face of the ingot, wherein the plurality of discharge channels comprises: first discharge channels configured to receive the coolant at a first flow rate; and second discharge channels configured to receive the coolant at a second flow rate, wherein the second flow rate is different from the first flow rate.

[0062] Illustration 13. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, further comprising controllers within each of the first discharge channels such that that the coolant is received at the first flow rate, wherein the controllers comprise one or more of sleeves, wires, or inserts.

[0063] Illustration 14. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, further comprising controllers within each of the first discharge channels such that that the coolant is received at the first flow rate, wherein the controllers are first controllers, and wherein the direct chill casting system further comprises second controllers at least partially within each of the second discharge channels and such that the coolant is received at the second flow rate.

[0064] Illustration 15. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the first controllers and the second controllers each comprise one or more of sleeves, wires, or inserts.

[0065] Illustration 16. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the first controllers and the second controllers are a same type of controller.

[0066] Illustration 17. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, further comprising controllers within each of the first discharge channels such that that the coolant is received at the first flow rate, wherein at least one of the controllers is removable from the corresponding first discharge channel.

[0067] Illustration 18. A direct chill casting system comprising a mold for forming an ingot having opposing rolling faces, wherein the mold defines an open-ended casting cavity having a casting axis and comprises a plurality of discharge channels configured to discharge coolant onto a first rolling face of the opposing rolling faces of the ingot, wherein the plurality of discharge channels comprises first discharge channels and second discharge channels, and wherein a flow rate of coolant through the first discharge channels is adjustable and such that the flow rate of coolant from the first discharge channels is different from the flow rate of coolant from the second discharge channels.

[0068] Illustration 19. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, further comprising controllers at least partially within the first discharge channels and such that the flow rate of coolant from the first discharge channels is different from the flow rate of coolant from the second discharge channels.

[0069] Illustration 20. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the controllers comprise one or more of sleeves, wires, or inserts.

[0070] Illustration 21. The direct chill casting system of any preceding or subsequent illustration or combination of illustrations, wherein the flow rate of coolant through the first discharge channels is automatically adjustable.

[0071] Illustration 22. A method of casting an ingot, the method comprising: receiving molten metal in the casting cavity defined by the mold of any preceding or subsequent illustration or combination of illustrations and causing a bottom block to move away from a lower end of the mold, wherein the bottom block initially closes the lower end of the mold cavity; and discharging coolant from a plurality of discharge channels of the mold at varying flow rates onto a rolling face of the ingot emerging from the mold as the bottom block moves away from the lower end of the mold by varying the flow rate of coolant received by the plurality of discharge channels.

[0072] Illustration 23. A direct chill casting system comprising a mold for forming an ingot, wherein the mold defines an open-ended casting cavity with a casting axis and further comprises at least one discharge channel configured to discharge coolant onto the ingot, wherein: the discharge channel comprises a plurality of input apertures for receiving the coolant and a plurality of discharge apertures for discharging the coolant, wherein the plurality of input apertures are fluidly connected to the plurality of discharge apertures; a first input aperture of the plurality of input apertures is configured to receive the coolant at a first flow rate; and a second input aperture of the plurality of input apertures is configured to receive the coolant at a second flow rate different from the first flow rate.

[0073] Illustration 24. A direct chill casting system comprising: a mold for forming an ingot, wherein the mold defines an open-ended casting cavity having a casting axis and wherein the mold comprises at least one discharge channel configured to discharge coolant onto the ingot, wherein the at least one discharge channel comprises a plurality of input apertures and of discharge apertures fluidly connected to the plurality of input apertures; and a controller at least partially within at least one input aperture of the plurality of input apertures of the at least one of discharge channel such that a flow rate of coolant discharged by the at least one input aperture is different from a flow rate of coolant from another input aperture of the at least one discharge channel.

[0074] Illustration 25. A direct chill casting system comprising: a mold for forming an ingot, wherein the mold defines an open-ended casting cavity having a casting axis and wherein the mold comprises at least one discharge channel configured to discharge coolant onto a rolling face of the ingot, wherein the at least one discharge channel comprises: first input apertures configured to receive the coolant at a first flow rate; and second input apertures configured to receive the coolant at a second flow rate, wherein the second flow rate is different from the first flow rate.

[0075] The subject matter of embodiments of the present disclosure is described here with specificity to meet statutory requirements, but this description is not necessarily intended to limit the scope of the claims. The claimed subject matter may be embodied in other ways, may include different elements or steps, and may be used in conjunction with other existing or future technologies. This description should not be interpreted as implying any particular order or arrangement among or between various steps or elements except when the order of individual steps or arrangement of elements is explicitly described. Directional references such as "up," "down," "top," "bottom," "left," "right," "vertical," "horizontal," "lateral," "longitudinal," "front," and "back," among others, are intended to refer to the orientation as illustrated and described in the figure (or figures) to which the components and directions are referencing.

[0076] The terms "comprising," "having," "including," and "containing" are to be construed as open-ended terms (i.e., meaning "including, but not limited to,") unless otherwise noted. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, or gradients thereof, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate embodiments of the invention, and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

[0077] The above-described aspects are merely possible examples of implementations, merely set forth for a clear understanding of the principles of the present disclosure. Many variations and modifications can be made to the above-described embodiment(s) without departing substantially from the spirit and principles of the present disclosure. All such modifications and variations are intended to be included herein within the scope of the present disclosure, and all possible claims to individual aspects or combinations of elements or steps are intended to be supported by the present disclosure. Moreover, although specific terms are employed herein, as well as in the claims that follow, they are used only in a generic and descriptive sense, and not for the purposes of limiting the described embodiments, nor the claims that follow.

CLAIMS

That which is claimed:

1. A direct chill casting system comprising a mold for forming an ingot, wherein the mold defines an open-ended casting cavity with a casting axis and further comprises a plurality of discharge channels configured to discharge coolant onto the ingot, wherein:

each discharge channel of the plurality of discharge channels comprises an input aperture for receiving the coolant and a discharge aperture for discharging the coolant;

a first discharge channel of the plurality of discharge channels is configured to receive the coolant at a first flow rate; and

a second discharge channel of the plurality of discharge channels is configured to receive the coolant at a second flow rate different from the first flow rate.

2. The direct chill casting system of claim 1, further comprising a controller at least partially within the input aperture of the first discharge channel and such that the coolant is received in the first discharge channel at the first flow rate.

3. The direct chill casting system of claim 2, wherein the controller comprises at least one of a sleeve, a wire, or an insert.

4. The direct chill casting system of claim 2, wherein the controller is a first controller, and wherein the direct chill casting system further comprises a second controller at least partially within the input aperture of the second discharge channel and such that the coolant is received in the second discharge channel at the second flow rate.

5. The direct chill casting system of claim 1, wherein the plurality of discharge channels comprises a plurality of first discharge channels and a plurality of second discharge channels, wherein the plurality of first discharge channels are configured to discharge coolant on a first portion of a rolling face of the ingot, and wherein the plurality of second discharge channels are configured to discharge coolant on a second portion of the rolling face of the ingot.

6. The direct chill casting system of claim 1, wherein the plurality of first discharge channels and the plurality of second discharge channels are arranged in the mold such that on overall flow rate of coolant discharged across a rolling face of the ingot is non-uniform.

7. A direct chill casting system comprising:
a mold for forming an ingot, wherein the mold defines an open-ended casting cavity having a casting axis and wherein the mold comprises a plurality of discharge channels configured to discharge coolant onto the ingot; and
a controller at least partially within a first discharge channel of the plurality of discharge channels such that a flow rate of coolant discharged by the first discharge channel is different from a flow rate of coolant from a second discharge channel of the plurality of discharge channels.

8. The direct chill casting system of claim 7, wherein the controller comprises at least one of a sleeve, a wire, or an insert.

9. The direct chill casting system of claim 7, wherein the controller is removable from the first discharge channel.

10. The direct chill casting system of claim 7, wherein the controller is at least partially within the first discharge channel such that the flow rate of coolant received by the first discharge channel is less than the flow rate of coolant received by the second discharge channel.

11. The direct chill casting system of claim 7, wherein the controller is a first controller of a plurality of controllers, wherein each controller of the plurality of controllers is positioned at least partially within a corresponding discharge channel of the plurality of discharge channels.

12. A direct chill casting system comprising:
a mold for forming an ingot, wherein the mold defines an open-ended casting cavity having a casting axis and wherein the mold comprises a plurality of discharge channels

configured to discharge coolant onto a rolling face of the ingot, wherein the plurality of discharge channels comprises:

first discharge channels configured to receive the coolant at a first flow rate; and

second discharge channels configured to receive the coolant at a second flow rate, wherein the second flow rate is different from the first flow rate.

13. The direct chill casting system of claim 12, further comprising one or more controllers within each of the first discharge channels such that that the coolant is received at the first flow rate, wherein the controllers comprise one or more of sleeves, wires, or inserts.

14. The direct chill casting system of claim 12, further comprising one or more controllers within each of the first discharge channels such that that the coolant is received at the first flow rate, wherein the one or more controllers are first controllers, and wherein the direct chill casting system further comprises one or more second controllers at least partially within each of the second discharge channels and such that the coolant is received at the second flow rate.

15. The direct chill casting system of claim 14, wherein the first controllers and the second controllers each comprise one or more of sleeves, wires, or inserts.

16. The direct chill casting system of claim 15, wherein the first controllers and the second controllers are a same type of controller.

17. The direct chill casting system of claim 12, further comprising one or more controllers within each of the first discharge channels such that that the coolant is received at the first flow rate, wherein at least one of the one or more controllers is removable from a corresponding first discharge channel.

18. A direct chill casting system comprising a mold for forming an ingot having opposing rolling faces,

wherein the mold defines an open-ended casting cavity having a casting axis and wherein the mold comprises a plurality of discharge channels configured to discharge coolant onto a first rolling face of the opposing rolling faces of the ingot,

wherein the plurality of discharge channels comprises first discharge channels and second discharge channels, and

wherein a flow rate of coolant through the first discharge channels is adjustable and such that the flow rate of coolant from the first discharge channels is different from the flow rate of coolant from the second discharge channels.

19. The direct chill casting system of claim 18, further comprising one or more controllers at least partially within the first discharge channels and such that the flow rate of coolant from the first discharge channels is different from the flow rate of coolant from the second discharge channels.

20. The direct chill casting system of claim 19, wherein the one or more controllers comprise one or more of sleeves, wires, or inserts.

21. The direct chill casting system of claim 18, wherein the flow rate of coolant through the first discharge channels is automatically adjustable.

22. A method of casting an ingot, the method comprising:

receiving molten metal in a casting cavity defined by a mold and causing a bottom block to move away from a lower end of the mold, wherein the bottom block initially closes the lower end of the mold cavity; and

discharging coolant from a plurality of discharge channels of the mold at varying flow rates onto a rolling face of the ingot emerging from the mold as the bottom block moves away from the lower end of the mold by varying the flow rate of coolant received by the plurality of discharge channels.

23. A direct chill casting system comprising a mold for forming an ingot, wherein the mold defines an open-ended casting cavity with a casting axis and further comprises at least one discharge channel configured to discharge coolant onto the ingot, wherein:
the discharge channel comprises a plurality of input apertures for receiving the coolant and a plurality of discharge apertures for discharging the coolant, wherein the plurality of input apertures are fluidly connected to the plurality of discharge apertures;
a first input aperture of the plurality of input apertures is configured to receive the coolant at a first flow rate; and
a second input aperture of the plurality of input apertures is configured to receive the coolant at a second flow rate different from the first flow rate.

24. A direct chill casting system comprising:
a mold for forming an ingot, wherein the mold defines an open-ended casting cavity having a casting axis and wherein the mold comprises at least one discharge channel configured to discharge coolant onto the ingot, wherein the at least one discharge channel comprises a plurality of input apertures and of discharge apertures fluidly connected to the plurality of input apertures; and
a controller at least partially within at least one input aperture of the plurality of input apertures of the at least one of discharge channel such that a flow rate of coolant discharged by the at least one input aperture is different from a flow rate of coolant from another input aperture of the at least one discharge channel.

25. A direct chill casting system comprising:
a mold for forming an ingot, wherein the mold defines an open-ended casting cavity having a casting axis and wherein the mold comprises at least one discharge channel configured to discharge coolant onto a rolling face of the ingot, wherein the at least one discharge channel comprises:
first input apertures configured to receive the coolant at a first flow rate; and
second input apertures configured to receive the coolant at a second flow rate, wherein the second flow rate is different from the first flow rate.

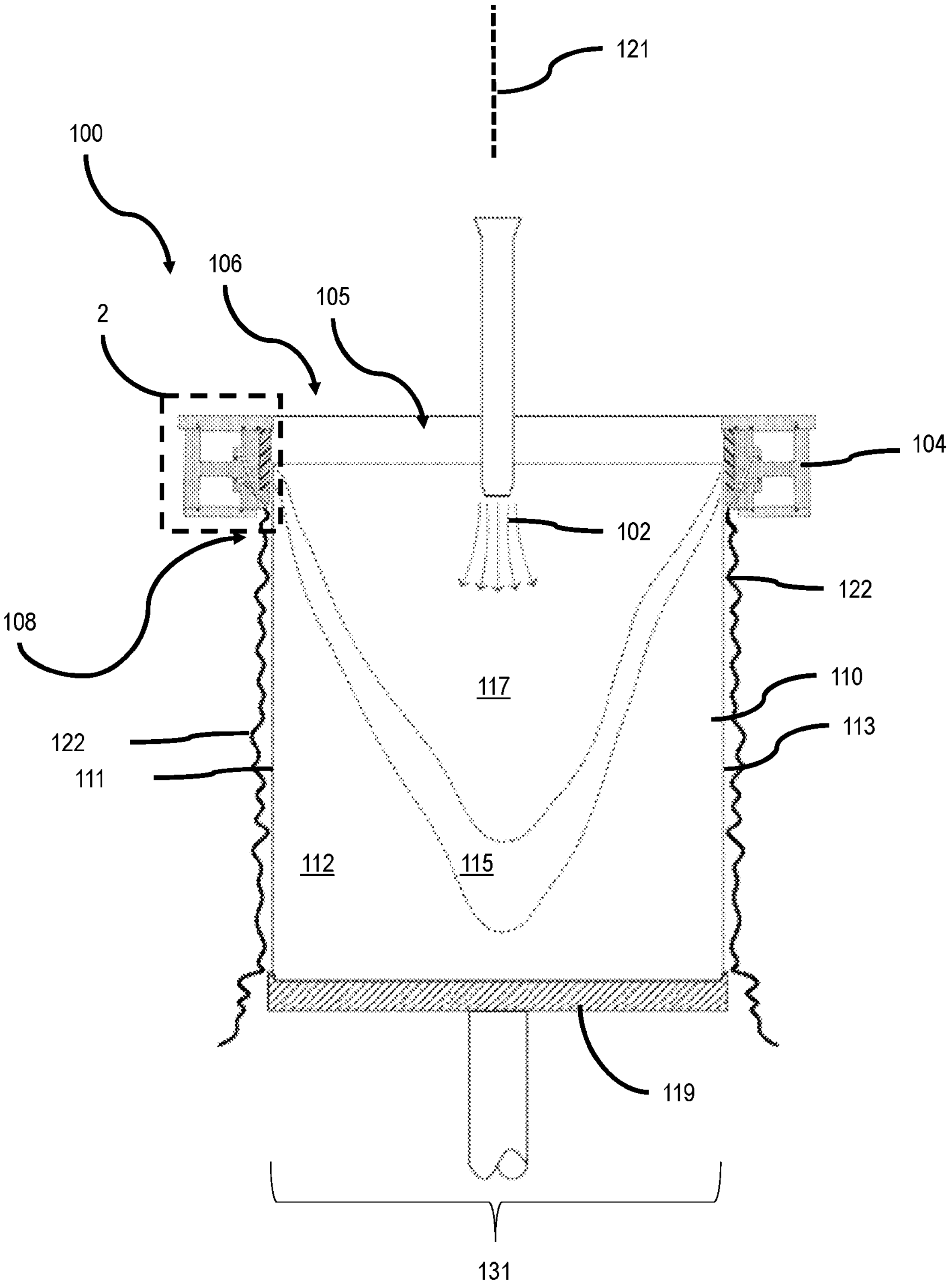
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FIG. 1

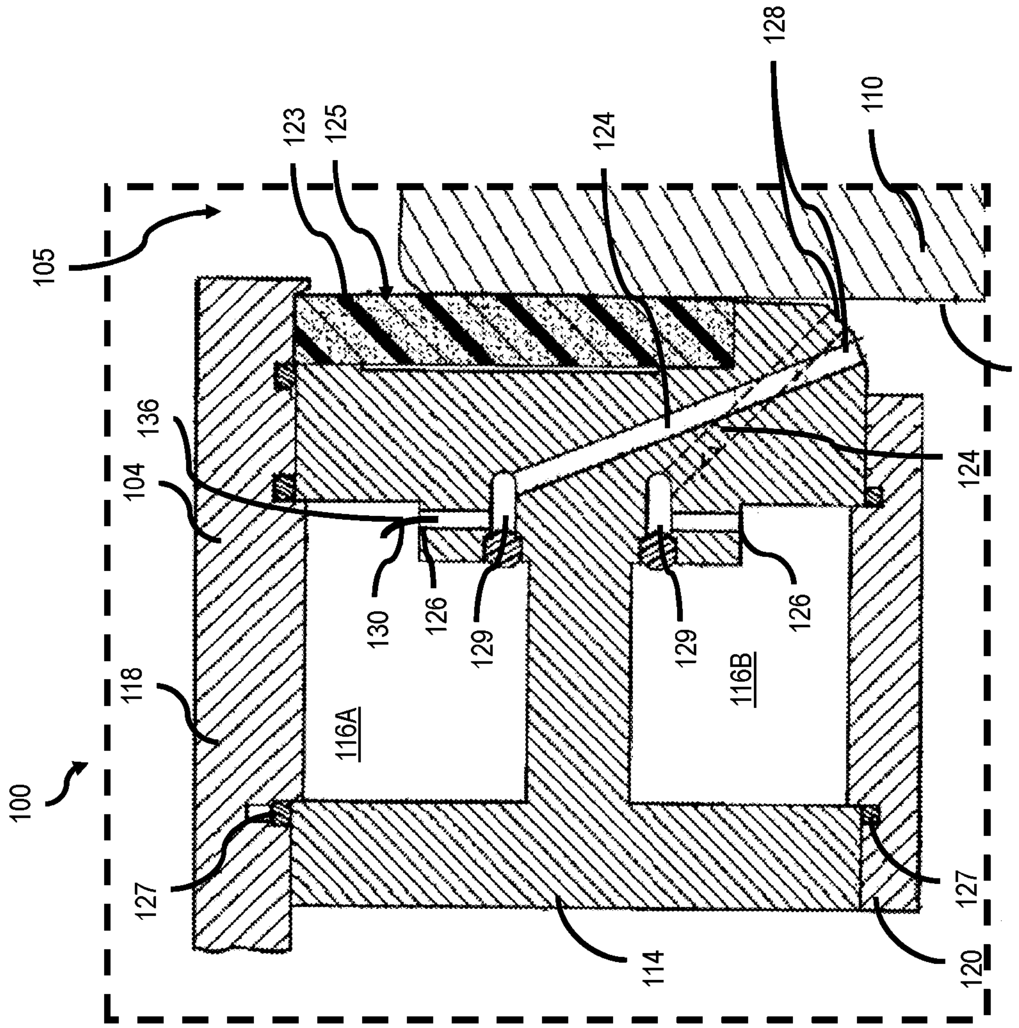
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FIG. 2

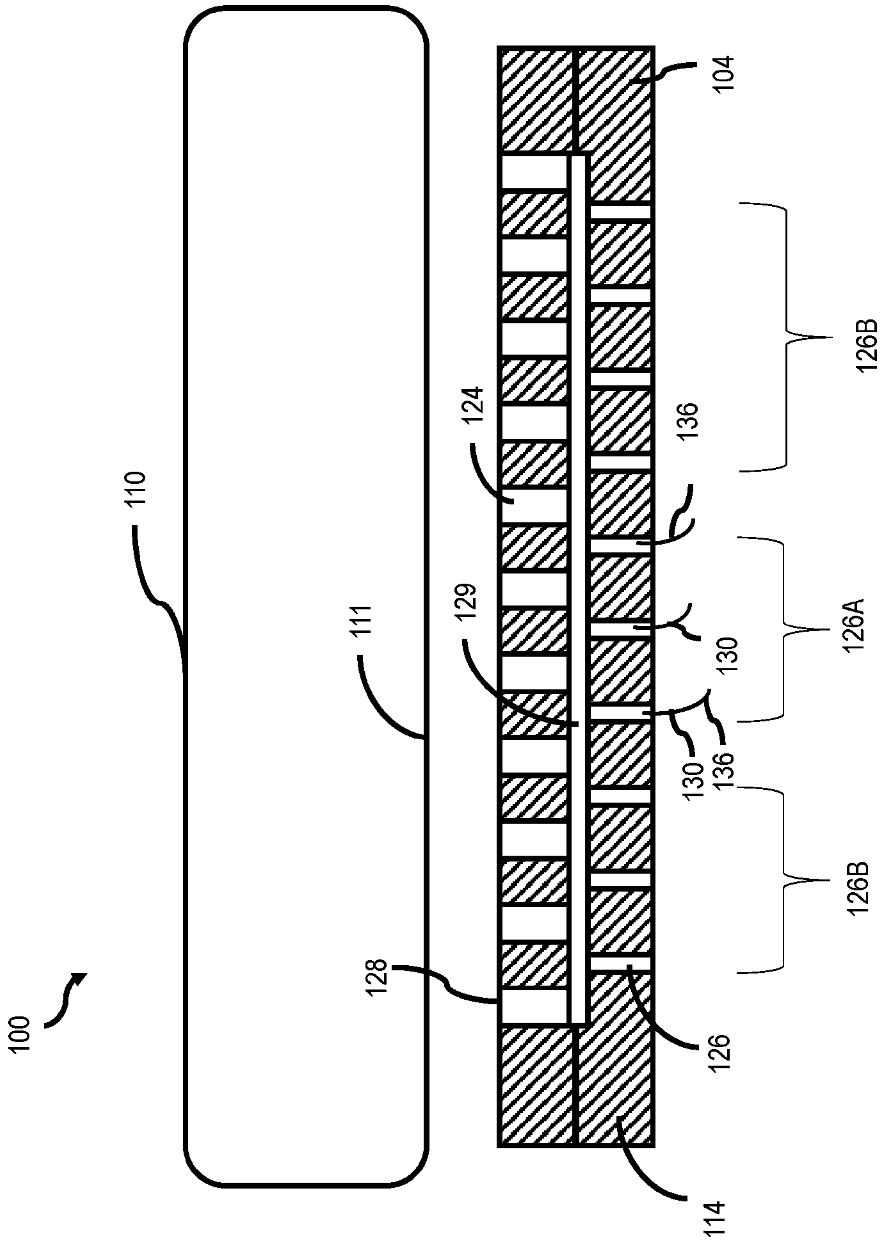
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FIG. 3

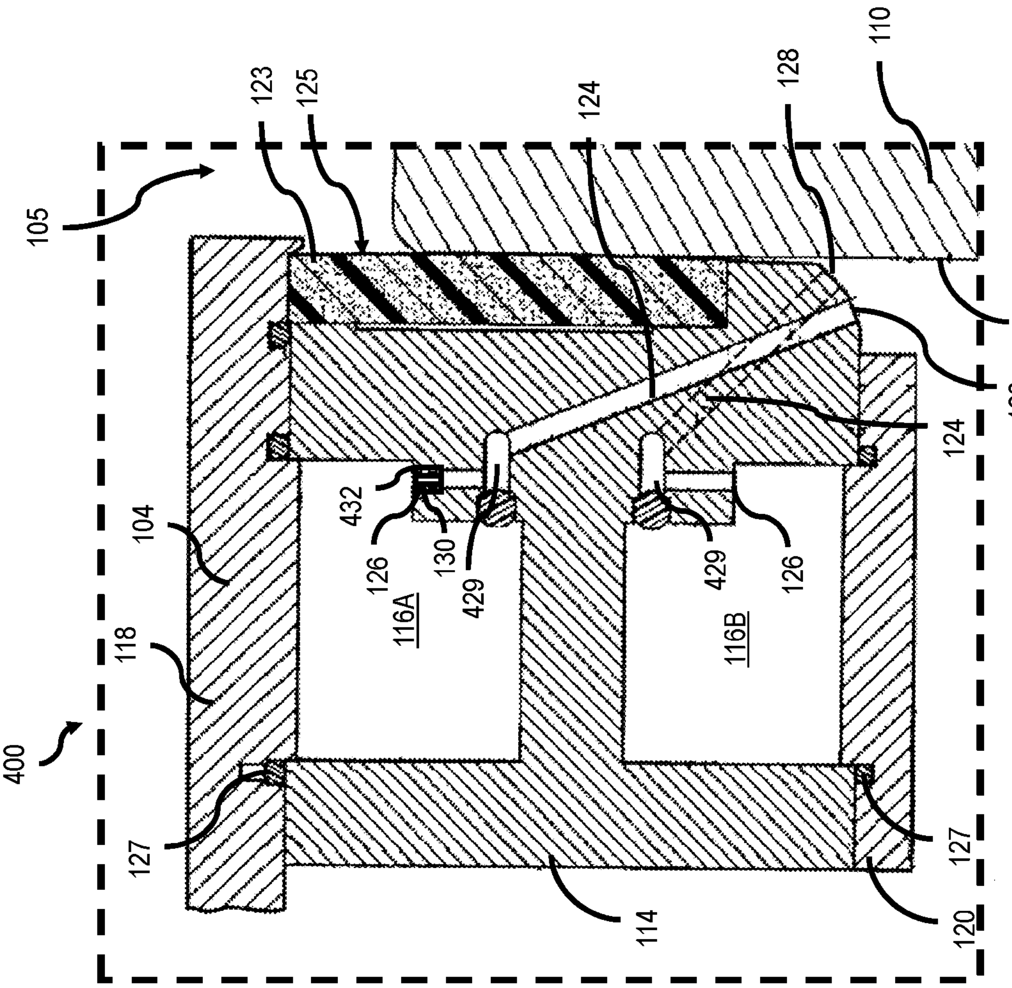
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FIG. 4

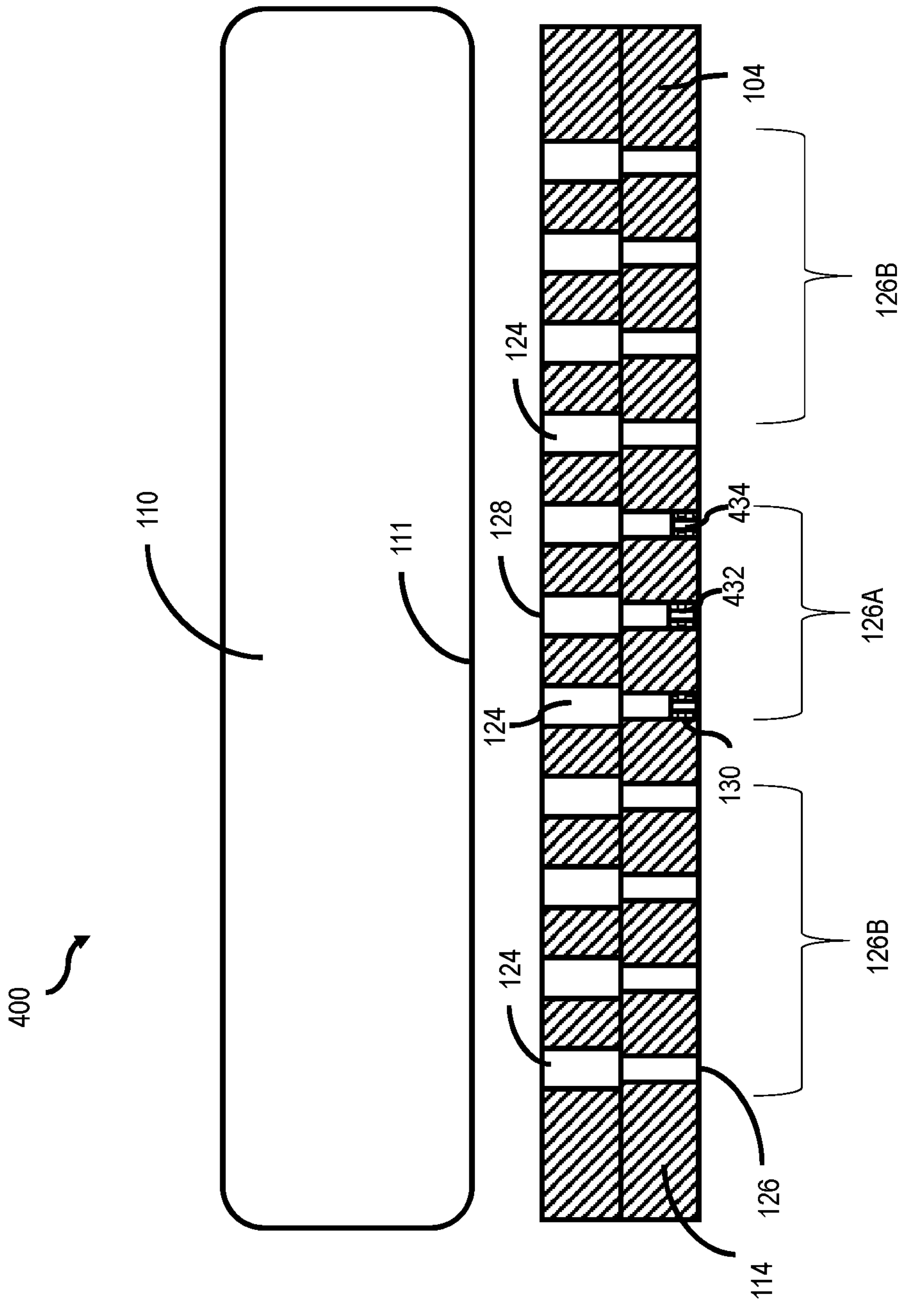
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FIG. 5

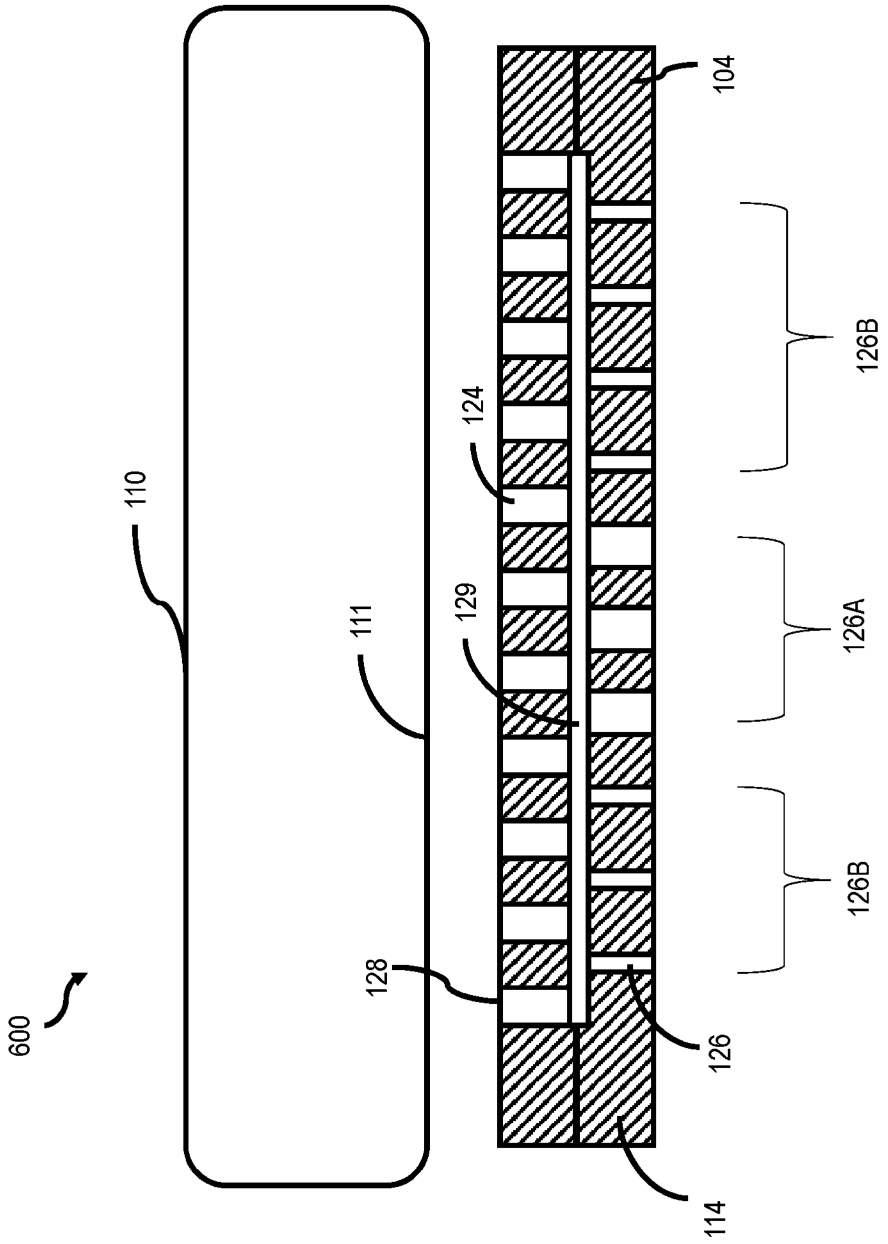

FIG. 6

710A

751A

FIG. 7A

710B

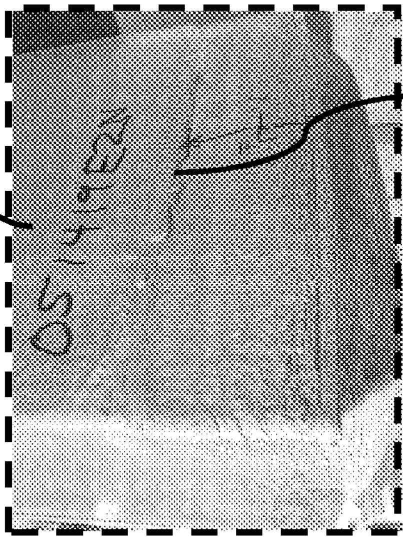

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FIG.7B

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2025/010034

A. CLASSIFICATION OF SUBJECT MATTER
INV. B22D11/049 B22D11/055 B22D11/22
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)
B22D

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 2002/174971 A1 (LANGLAIS JOSEPH [CA] ET AL) 28 November 2002 (2002-11-28) paragraphs [0002], [0013] - [0015], [0034] - [0036], [0039] - [0040], [0050] - [0053], [0065]; claims 1-21; figures 1-3,10,11	1-25
A	US 2012/241118 A1 (WAGSTAFF ROBERT BRUCE [US] ET AL) 27 September 2012 (2012-09-27) the whole document	1-25
A	US 2023/219130 A1 (WOMACK RANDAL GUY [US] ET AL) 13 July 2023 (2023-07-13) the whole document	1-25
A	US 7 007 739 B2 (WAGSTAFF INC [US]) 7 March 2006 (2006-03-07) the whole document	1-25

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"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

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"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
1 April 2025	10/04/2025

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

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2025/010034

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