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CONTINUOUS CASTING OF MULTI-ALLOY METAL PRODUCTS AND RELATED METHODS

[0001] FIG. 1 provides a schematic illustration of a metal product comprising a plurality of metal alloy layers consecutively distributed along a width of the metal product.

[0002] FIG. 2 provides a schematic illustration of a metal product comprising a plurality of metal alloy layers consecutively distributed along a thickness of the metal product.

[0003] FIG. 3 provides a schematic illustration of continuously casting a metal product, depicting a plurality of injectors consecutively distributed along a length of a pair of moving opposed casting surfaces.

[0004] FIG. 4 provides a schematic illustration of continuously casting a metal product, depicting a plurality of injectors consecutively distributed along a casting width of a pair of moving opposed casting surfaces.

[0005] FIG. 5 provides a cross-sectional illustration of continuously casting a metal product, depicting a plurality of injectors consecutively distributed along a casting width of a pair of moving opposed casting surfaces.

[0006] FIG. 6 provides a schematic overview of continuously casting a multiple metal alloy.

[0007] FIG. 7 provides a flow diagram of a method for continuous casting a metal product comprising a plurality of metal alloy layers.

DETAILED DESCRIPTION

[0008] Metal products can include a plurality of different metal alloys. The plurality of metal alloys may be bonded together to form layers of metal alloys of independent compositions that extend the length of the metal product. The layers may be distributed along the thickness of the metal product (i.e., in a sandwich configuration) or may be distributed along the width of the metal product.

[0009] Spatially varying the composition of the metal product provides numerous advantages. One advantage relates to the ability to create a metal product that has a variety of characteristics within the product. For example, a metal product may be generated with different strength and formability characteristics at different locations throughout the product. By generating a metal product including layers of independent metal alloys, characteristics of the metal product can be varied at different locations throughout the metal product by adjusting or selecting the composition of the different layers to match a target property spatial distribution for the metal product.

[0010] The varying characteristics of the metal product may arise from metallurgically bonding multiple independent metal alloys to one another. The conditions under which the multiple metal alloys are bonded together can be advantageously controlled to form diffusion zones or to instead clearly delineate directly adjacent metal alloys. In some embodiments, diffusion zones at the interfaces of directly adjacent metal alloys may be manipulated to create a gradient of a desired characteristic. In other embodiments, the diffusion zones may be manipulated to be indistinguishable from the metal alloys so as to clearly delineate one metal alloy from directly adjacent metal alloys. In some cases, adjacent metal alloys may have only slight compositional variations, although the total compositional variation across the entire set of metal alloys may be substantial. By metallurgically bonding the different metal alloys to one another, strong bonds can be formed between the different metal alloys, providing for robust metal products that have spatially variable compositions, useful for a variety of applications.

[0011] The customization capabilities of the disclosed metal alloy products provide extensive benefits and the ability to generate metal products of rich compositional complexity. For example, the disclosed metal alloy products may allow for more efficient product processing. In particular, it may be desirable for a metal product, such as a metal sheet, to have high strength at its center but high formability characteristics at its edges. Such a configuration may be useful for automobile body panels, as these products may be hemmed at their edges (for which high formability properties are advantageous) and have target strength specifications for the center regions. By generating a metal product having a compositional variation across its width, for example, these parameters can be met. Advantageously, customization of a metal product's characteristics at discrete geometrical positions by way of compositional variations may provide decreased processing time and complexity.

[0012] FIG. 1 illustrates a metal product 100. Metal product 100 may be a plate, a shate, or a sheet. Metal product 100 may be or comprise a composite substrate formed by a continuous casting process in which different alloys are metallurgically bonded within a single substrate. Herein, the term metal product may be interchangeable and coextensive with the term composite metal product. The continuous casting process may employ a pair of moving opposed casting surfaces configured to move in casting direction 190. Casting direction 190 identifies the casting direction in relation to metal product 100. Casting direction 190 may correspond to the direction that metal product 100 is moved through the casting surfaces during the casting process. In embodiments, metal product 100 may be subjected to one or more hot rolling or cold rolling processes/operations following casting in the continuous casting process.

[0013] As noted above, metal product 100 may be a composite substrate, such as a composite substrate comprising a plurality of layers. Metal product 100 as illustrated in FIG. 1 comprises layer 112, layer 114, and layer 116. Each layer 112, 114, 116 may correspond to an independent metal alloy that is distinct from the metal alloys of directly adjacent layers, although they need not. For example, layer 112 corresponds to metal alloy 102, layer 114 corresponds to metal alloy 104, and layer 116 corresponds to metal alloy 106, with at least one of metal alloys 102, 104, and 106 being distinct metal alloys from another of metal alloys 102, 104, and 106.

[0014] In some embodiments, metal alloys 102, 104, and 106 are all different metal alloys from each other. For example, metal alloy 102 may be a first 6xxx series aluminum alloy, metal alloy 104 may be a second 6xxx series aluminum alloy, and metal alloy 106 may be a first 5xxx series aluminum alloy. In other embodiments, only a subset of metal alloys 102, 104, and 106 may be different metal alloys from each other. As one example, only directly adjacent metal alloys may be different, such as where metal alloys 102, 104, and 106 alternate or have any suitable pattern or arrangement. For example, metal alloy 102 and metal alloy 106 may both be a first 6xxx series aluminum alloy, but metal alloy 104, which is directly adjacent to both metal alloy 102 and metal alloy 106, may be a second 6xxx series aluminum alloy. Although 5xxx series aluminum alloys and 6xxx series aluminum alloys are provided in the above description as examples, other aluminum alloys may be employed, such as one or more 1xxx series aluminum alloys, 2xxx series aluminum alloys, 3xxx series aluminum alloy, 4xxx series aluminum alloy, 5xxx series aluminum alloys, 6xxx series aluminum alloys, 7xxx series aluminum alloys, or 8xxx series aluminum alloys.

[0015] Optionally, metal alloys 102, 104, and 106 may be aluminum alloys, or magnesium alloys. In embodiments, all three metal alloys 102, 104, and 106 may be from the same element alloy family, such as all three metal alloys 102, 104, and 106 being aluminum alloys, or all three metal alloys 102, 104, and 106 being magnesium alloys. In other embodiments, metal alloys

102, 104, 106 may come from a mixture of element alloy families, such as where each of metal alloys 102, 106, may be an aluminum alloy or a magnesium alloy, for example.

[0016] As illustrated in FIG. 1, metal product 100 comprises three layers of metal alloys. In embodiments, the number of layers forming metal product 100 may be more or less than three. For example, metal product 100 may comprise up to 10 layers of metal alloys, or more. The number of layers of metal alloys may optionally range from 3 up to 10, from 10 up to 20, or from 20 up to 50 layers. In some cases, metal product 100 has two layers of distinct metal alloys. In various embodiments, the number of layers of metal alloys in a metal product may be from 3 to 50, from 5 to 50, from 10 to 50, from 15 to 50, from 20 to 50, from 25 to 50, from 30 to 50, from 35 to 50, from 40 to 50, from 45 to 50, from 3 to 45, from 5 to 45, from 10 to 45, from 15 to 45, from 20 to 45, from 25 to 45, from 30 to 45, from 35 to 45, from 40 to 45, from 3 to 40, from 5 to 40, from 10 to 40, from 15 to 40, from 20 to 40, from 25 to 40, from 30 to 40, from 35 to 40, from 3 to 35, from 5 to 35, from 10 to 35, from 15 to 35, from 20 to 35, from 25 to 35, from 30 to 35, from 3 to 25, from 5 to 25, from 10 to 25, from 15 to 25, from 20 to 25, from 3 to 20, from 5 to 20, from 10 to 20, from 15 to 20, from 3 to 15, from 5 to 15, from 10 to 15, from 3 to 10, from 5 to 10, or from 3 to 5. For example, metal product 100 may comprise up to 20 layers, wherein each layer independently comprises one of up to 20 metal alloys.

[0017] Layers 112, 114, and 116 may extend an entire length of metal product 100, such as an entire length of the metal product 100 along casting direction 190. In some embodiments, one or more layers may not extend the entire length of metal product 100. For example, metal product 100 may have 4 or more layers of metal alloys 102, 104, 106, and a fourth alloy (not shown) at a starting end and only three or more layers of metal alloys 102, 104, and 106 at a terminating end. The starting end may correspond to an end of metal product 100 that is processed at the beginning of the continuous casting cycle and the terminating end may correspond to the end of metal product 100 processed at the end of the continuous casting cycle and/or cut by a cutting device to cleave metal product 100. To achieve a non-uniform number of layers at the metal product's two ends, metal alloys in a molten state may be initially injected into the continuous casting system, however, at a designated time, the injecting of one or more of the metal alloys may be ceased to reduce the number of layers in a composite substrate. In some cases, additional volume of other metals from other injectors may be used to provide a continuous volume flow into the casting cavity. In other embodiments, instead of reducing the number of layers of metal alloys between the starting end and the terminating end of a composite substrate, the inverse may be achieved. For example, metal product 100 may have only three or more layers of metal alloys 102, 104, and 106 at a starting end but may have four or more layers of metal alloys 102, 104, 106, and a fourth alloy (not shown) at the terminating end. This may be achieved by introducing metal alloys in a molten phase into the casting system after the process cycle of metal product 100 has already begun.

[0018] As illustrated in FIG. 1, layers 112, 114, and 116 may be distributed consecutively adjacent to each other. For example, layer 112 may be positioned directly adjacent to layer 114 and layer 114 may be positioned directly adjacent to layer 116. As used herein, the phrase "directly adjacent" means that at least one interface of the referenced objects (e.g., layers) is a shared interface. For example, layer 112 and layer 114 are directly adjacent to each other because they share an interface.

[0019] Layers 112, 114, and 116 may also be consecutively arranged in the same plane. For example, as illustrated in FIG. 1, layers 112, 114, and 116 may be consecutively arranged in the same plane perpendicular to casting direction. Layers 112, 114, and 116 may also be positioned as to be linear to each other. In such embodiments, layers 112, 114, and 116 may be linearly distributed in a plane perpendicular to casting direction 190. Although layers 112, 114, and 116 are illustrated in FIG. 1 as having constant widths, embodiments are contemplated where the widths of individual layers may change along the casting direction, and such a configuration may be achieved by modifying a volume of molten alloy injected into a casting cavity, for example.

[0020] Optionally, layers 112, 114, and 116 may be distributed perpendicular to the casting direction along the width of metal product 100, as illustrated in FIG. 1. In embodiments where layers 112, 114, and 116 are distributed along the width of metal product 100, each layer may be exposed to the opposed casting surfaces during the casting process. To be exposed to the casting surfaces during the casting process may mean that each layer comes in direct contact with the casting surfaces.

[0021] In contrast, in embodiments where the layers are distributed along the thickness of the metal product, as illustrated and discussed in further detail with respect to FIG. 2, not all the layers may be exposed to the opposed casting surfaces. Instead, for the embodiments where the layers are distributed along the thickness of metal product, only the outer most layers may be exposed to the opposed casting surfaces.

[0022] Diffusion between directly adjacent layers may occur during the casting process. Diffusion of components of adjacent metal alloys may provide additional variation to the characteristics of metal product 100. Without being bound by any theory, it is believed that during the casting process, as a first metal alloy and a second adjacent metal alloy come in contact and begin to bond with each other, material of the second adjacent metal alloy may diffuse into the first metal alloy, and material of the first metal alloy may diffuse into the second adjacent metal alloy. The rate and extent that a first metal alloy from a first layer may diffuse into a second adjacent layer comprising a second metal alloy may depend on the composition of each metal alloy, the properties of each metal alloy, the temperature of each alloy, and the like. For example, density differences between the first and second metal alloys may impact the rate and extent of diffusion. Other properties that may impact the rate and extent of diffusion include diffusion coefficients, eutectic points and compositions, the temperature of the interfaces of the metal alloys, particle size formation during the cooling of the metal alloys, and the like.

[0023] As illustrated in FIG. 1, diffusion zones 120A, 120B, 120C, and 120D may occur at the interfaces between layers 112, 114, and 116. Diffusion zones 120A and 120B may form at the interface between metal alloy 102 and metal alloy 104. Diffusion zone 120A may comprise components of metal alloy 102 with diffused material of metal alloy 104. Similarly, diffusion zone 120B may comprise metal alloy 104 with diffused material of metal alloy 102. As noted above, the amount of diffused material of metal alloy 104 within diffusion zone 120A may depend on the physical, chemical, and thermodynamic properties of metal alloy 102 and metal alloy 104. Similarly, the amount of diffused material of metal alloy 102 within diffusion zone 120B may depend on the physical, chemical, and thermodynamic properties of metal alloy 102 and metal alloy 104.

[0024] Diffusion zones 120C and 120D may form at the interface between metal alloy 104 and metal alloy 106. Diffusion zone 120C may comprise components of metal alloy 104 with diffused material of metal alloy 106. Similarly, diffusion zone 120D may comprise components of metal alloy 106 with diffused material of metal alloy 104. Again, the amount of diffused material of metal alloy 106 within diffusion zone 120C, and the amount of diffused material of metal alloy 104 within diffusion zone 120D, may depend on the physical, chemical and thermodynamic properties of metal alloys 104 and 106.

[0025] Diffusion zones 120A, 120B, 120C, and 120D may extend at the interfaces between layers 112, 114, and 116 along metal product 100 in casting direction 190. In some embodiments, diffusion zones 120A, 120B, 120C, and 120D may extend the entire length of metal product 100. In other embodiments, diffusion zones 120A, 120B, 120C, and 120D may extend only a portion of the length of metal product 100. Optionally, one or more of the diffusion zones 120A, 120B, 120C, and 120D may extend the entire length of metal product 100 while the remaining diffusion zones extend only a portion of the length of metal product 100. For example, diffusion zone 120A and 120B may extend the entire length of metal product 100 while diffusion zones 120C and 120D may extend only a portion or fraction of the total length of metal product 100.

[0026] Similar to metal alloys 102, 104, and 106, diffusion zones 120A, 120B, 120C, and 120D may impart various chemical and physical properties to metal product 100. Diffusion zones 120A, 120B, 120C, and 120D may exhibit one or more desired characteristics, such as increased tensile strength, malleability, loading, or stress capacities. The rate and extent of each diffusion zone and each diffusion zone's expressed properties may be manipulated through controlling the interface temperature between each metal alloy during bonding and casting. Controlling the temperature of the metal alloy interfaces will be discussed in further detail below. Other desired diffusion zone characteristics may be achieved through precise selection of adjacent metals to emphasize properties, such as, for example, density differences, diffusion coefficients, or eutectic properties.

[0027] In various embodiments, no diffusion zones may be formed. Instead, metal product 100 may comprise distinct layers of metal alloys 102, 104, and 106 directly metallurgically bonded to one another. While trace amounts of material may still diffuse from one metal alloy to a directly adjacent metal alloy during cooling and bonding, the amount of material diffused into the adjacent metal alloy may be considered negligible, resulting in no distinguishable change in characteristics or properties, such as physical, chemical, or electrical, to either of the directly adjacent metal alloys. In these embodiments, each layer of metal alloys remains distinct in its physical, chemical, and electrical properties from one or more directly adjacent layers.

[0028] Any one or more of layers 112, 114, or 116 may have a composition that varies across one or more dimensions, such as dimensions perpendicular to a casting direction. For example, in embodiments where the layers 112, 114, and 116 are distributed perpendicular to the casting direction along the width of metal product 100, the variation within layer 112, 114, or 116 may be along a width of metal product 100. As another example, in embodiments where the layers 112, 114, and 116 are distributed along the thickness of metal product 100, then the compositional variation within layer 112, 114, or 116 may be along a width of metal product 100. Compositional variation may include variations in both the macrostructure and microstructure of metal alloys 102, 104, and 106. For example, compositional variation of the macrostructure may include large grain sizes near the surface or edge of metal product 100, while the bulk or middle of metal product 100 comprise fine grain sizes. Exemplary compositional variation of the microstructure may include region at or near the surface or edge of metal product 100 having a composition that is different than the bulk composition.

[0029] Metallurgical bonds may form at the interfaces between layers 112, 114, and 116. "Metallurgical bond," as used herein, refers to an interface between two or more metals, metal alloys, or metal layers in a multi-component structure, such as metal product 100, where the interface chemically, mechanically, metallurgically, and electrically connects the different layers and is free or substantially free of any discontinuities, such as metal oxides, voids, or any form of discontinuities, that may otherwise disrupt the continuous bond. For example, an interface that is substantially free of discontinuities may include some amount of discontinuities that do not impact the strength, resiliency, or bonding effect of a metallurgical bond. In embodiments, metallurgical bonds are distinguished from mechanical bonds, which may explicitly incorporate discontinuities.

[0030] FIG. 2 provides a schematic illustration of metal product 200. Similar to metal product 100 illustrated in FIG. 1, metal product 200 may be a composite substrate formed by a continuous casting system. The continuous casting system may employ a pair of moving opposed casting surfaces configured to move in casting direction 290. As shown in FIG. 2, casting direction 290 identifies the casting direction in relation to metal product 200 and may correspond to the direction that metal product 200 is moved by the casting surfaces through the continuous casting process. Following the continuous casting process, metal product 200 may be subjected to one or more hot rolling or cold rolling processes. Metal product 200 may be a plate, a shate, or a sheet, for example.

[0031] Metal product 200 may be a composite substrate comprising a plurality of layers. As shown in FIG. 2, metal product 200 may be a composite substrate comprising three layers: layer

212, layer 214, and layer 216. Each of layers 212, 214, and 216 may correspond to a metal alloy that is distinct from directly adjacent metal alloys. For example, layer 212 may correspond to metal alloy 202, layer 214 may correspond to metal alloy 204, and layer 216 may correspond to metal alloy 206. As explained in more detail below, in some cases, metal alloy 202 and metal alloy 206 are the same, while metal alloy 204 is different. In other cases, all three metal alloys are different from one another.

[0032] In various embodiments, metal product 200 may be a composite substrate comprising more or less than three layers. For example, the composite substrate forming metal product 200 may have 10 layers of metal alloys, at least some of which are distinct from each other. The number of layers may optionally range from 3 up to 10, 10 up to 20, or 20 up to 50 layers. In various embodiments, the layers in a composite substrate may range from 3 up to 10, 5 up to 10, or 5 up to 50.

[0033] As illustrated in FIG. 2, layers 212, 214, and 216 may extend the entire length of metal product 200 in casting direction 290. However, in various embodiments, one or more of layers 212, 214, and 216 may not extend along the entire length of metal product 200. For example, metal product 200 may have four layers, each layer comprising metal alloys 202, 204, 206, and a fourth alloy (not shown), respectively, at a starting end of metal product 200 and extending along a portion of the length of metal product 200. Instead of extending the entire length of 200, one or more of the four layers of metal alloys 202, 204, 206, and a fourth layer (not shown) may discontinue before a cutting end of metal product 200. In such an embodiment, metal product 200 may have four layers of metal alloys 202, 204, 206, and a fourth layer (not shown) at the starting end of metal product 200 but only three layers of metal alloys 202, 204, and 206 at the cutting end of metal product 200.

[0034] To achieve a nonuniform distribution of layers, as discussed above, a plurality of metal alloys in a molten state, such as metal alloys 202, 204, 206, and a fourth alloy (not shown) may be initially introduced into the continuous casting system. However, at a designated time, the injecting of one or more of metal alloys 202, 204, 206, and a fourth alloy (not shown) may be discontinued to reduce the number of layers in the composite substrate. For example, at the beginning of the processing cycle for metal product 200, four metal alloys 202, 204, 206, and a fourth alloy (not shown) may be introduced into the continuous casting system; however, at a time during the processing cycle, the injection of metal alloy of the fourth layer (not shown) may be ceased to reduce the number of layers from four layers at the starting end of metal product 200 to three layers at the cutting end of metal product 200.

[0035] Similar to reducing the number of layers throughout a composite substrate, the number of layers may be increased between the starting end and the cutting end of metal product 200. In some embodiments, metal product 200 may have three layers of metal alloys 202, 204, and 206 at the starting end of the composite substrate but have four layers of metal alloys 202, 204, 206, and a fourth layer (not shown) at the cutting end of composite substrate. Instead of discontinuing injection of one or more metal alloys in the molten phase during the processing cycle of metal product 200, one or more metal alloys are introduced after the processing cycle has begun.

[0036] As noted above, each of layers 212, 214, and 216 may correspond to metal alloys 202, 204, and 206, respectively. In some embodiments, metal alloys 202, 204, and 206 may be different metal alloys from each other. For example, metal alloy 202 may be a first 5xxx series aluminum alloy, metal alloy 204 may be a second 5xxx series aluminum alloy, and metal alloy 206 may be a first 6xxx series aluminum alloy. In other embodiments, a portion of the layers 212, 214, and 216 may comprise the same metal alloys. For example, layer 212 may comprise metal alloy 202 that is a first 5xxx series aluminium alloy and layer 216 may comprise metal alloy 206 that is same first 5xxx series aluminum alloy as metal alloy 202. However, layer 214 comprising metal alloy 204 that is directly adjacent to both layers 212 and 216 may comprise a second 5xxx series aluminum alloy that is not the same as the first 5xxx series aluminum alloy. Although 5xxx series aluminum alloys and 6xxx series aluminum alloys are provided in the above discussion, other aluminum alloys may be employed. For example, metal alloys 202, 204, and 206 may be one or more 1xxx series aluminum alloy, 2xxx series aluminum alloy, 3xxx series aluminum alloy, 4xxx series aluminum alloy, 5xxx series aluminum alloy, 6xxx series aluminum alloy, 7xxx series aluminum alloy, or 8xxx series aluminum alloy.

[0037] Similar to the discussion with reference to FIG. 1, metal alloys 202, 204, and 206 may be aluminum alloys or magnesium alloys. In various embodiments, metal alloys 202, 204, and 206 may all be from the same element alloy family, such as, for example, the aluminum alloy family. In other embodiments, the metal alloys 202, 204, and 206 may come from one or more of the element family alloys. In other words, one or more of metal alloys 202, 204, and 206 may come from a different element family.

[0038] Layers 212, 214, and 216 may be distributed consecutively adjacent to each other. For example, as illustrated in FIG. 2, layer 212 may be positioned directly adjacent to layer 214, and layer 214 may be positioned directly adjacent to layer 216. In various embodiments, the distribution of layers 212, 214, and 216 may be linear to each other such that all three layers are arranged in the same plane. In some embodiments, layers 212, 214, and 216 may be distributed linearly in a plane perpendicular to casting direction 290.

[0039] Optionally, layers 212, 214, and 216 may be distributed perpendicular to casting direction 290 along the thickness of metal product 200. The thickness of a metal product being continuous cast may correspond to the separation distance between the casting surfaces. In some embodiments, a casting cavity of the continuous casting system may be defined by the separation distance between the casting surfaces. The overall thickness of metal product 200 may depend on whether metal product 200 is a plate, a shate, or a sheet. For example, in embodiments where metal product 200 is a plate, then the thickness may be greater than about 15 mm. In embodiments where metal product 200 is a shate, the thickness may be from about 4 mm to about 15 mm, for example. In embodiments where metal product 200 is a sheet, the thickness may be less than about 4 mm, for example. In general, metal product 200, as a product of a continuous casting process, may be referred to as a slab, and may be or be subjected to additional processing to generate a sheet, shate, or plate, for example.

[0040] A difference between the metal product 100 in FIG. 1, and the metal product 200 in FIG. 2 is the distribution of the layers. As noted above, in embodiments where layers 112, 114, and 116 are distributed along the width of metal product 100, each layer may be exposed to the opposed casting surfaces during the casting process. However, in embodiments where layers 212, 214, and 216 are distributed along the thickness, as opposed to the width, of metal product 200, as illustrated in FIG. 2, then not all the layers may be exposed to the opposed casting surfaces during casting. For example, for metal product 200, only layers 212 and 216 may be exposed to the opposed casting surfaces. Since layer 214 is interior to both layers 212 and 216, layer 214 may not be exposed to the opposed casting surfaces during the continuous casting process.

[0041] Diffusion between directly adjacent layers may occur during the casting process for metal product 200. As noted above, diffusion zones may provide variations to the characteristics of metal product 200. The rate and extent that diffusion zones occur may depend on the chemical, physical, electrical, and thermodynamic properties of the metal alloys interfacing each other.

[0042] As illustrated in FIG. 2, diffusion zones 220A, 220B, 220C, and 220D may occur at the interfaces between layers 212, 214, and 216. Diffusion zones 220A and 220B may form at the interface between metal alloy 202 and metal alloy 204. Diffusion zone 220A may comprise components of metal alloy 202 with material diffused from metal alloy 204. Diffusion zone 220B may comprise components of metal alloy 204 with material diffused from metal alloy 202. Similarly, diffusion zones 220C and 220D may form at the interface between metal alloy 204 and metal alloy 206. Diffusion zone 220C may comprise components of metal alloy 204 with material diffused metal alloy 206. Diffusion zone 220D may comprise components of metal alloy 206 with material diffused from metal alloy 204. As discussed above, the amount of diffused material and the rate at which the material diffuses may depend on the physical, chemical, and thermodynamic properties of metal alloys 202, 204, and 206, as well as the process conditions during the bonding of the interfacing metal alloys.

[0043] Optionally, in some embodiments, no diffusion zones may occur. Instead, metal product 200 may have distinct layers of metal alloy 202, 204, and 206. As noted above, while no diffusion zones may occur in these embodiments, it is appreciated that trace amounts of diffusion may still occur. However, the amount of diffused material in these embodiments may be considered negligible, resulting in no distinguishable change in either metal alloy. Instead, each layer of metal alloy may remain distinct from directly adjacent metal alloys in its physical, chemical, and electrical properties. At the interfaces between layers 212, 214, and 216, metallurgical bonds may form to create a continuous bond.

[0044] In various embodiments, any of layers 212, 214, or 216 may compositionally vary across one or more dimensions, such as one or more dimensions perpendicular to a casting direction. For example, in embodiments where the layers 212, 214, and 216 are distributed perpendicular to the casting direction along the width of metal product 200, the compositional variation within layer 212, 214, or 216 may along a width of metal product 200. As another example, in embodiments where the layers 212, 214, and 216 are distributed along the thickness of metal product 200, the compositional variation within layer 212, 214, or 216 may be along the thickness of metal product 200. Compositional variation may include variations in both the macrostructure and microstructure of metal alloys 202, 204, and 206. For example, compositional variation of the macrostructure may include large grain sizes near the surface or edge of metal product 200, while the bulk or middle of metal product 200 comprise fine grain sizes. Exemplary compositional variation of the microstructure may include a region at or near the surface or edge of metal product 200 having a composition that is different than the bulk composition.

[0045] It will be appreciated that the illustrated dimensions of metal product 100 and metal product 200 and the included components are not to scale and are illustrated for purposes of discussion only. Metal product 100, layers 112, 114, and 116, diffusion zones 120A, 120B, 120C, and 120D, metal product 200, layers 212, 214, and 216, and diffusion zones 220A, 220B, 220C, and 220D may have any suitable thickness, width, or length dimensions.

Methods of Producing the Metal Products

[0046] The metal products described herein can be advantageously cast according to the methods disclosed herein. As noted above, both metal products 100 and 200 may be formed via a continuous casting system. FIG. 3 provides a schematic illustration of continuous casting system 300 having three injectors consecutively distributed along a length of the opposed casting surfaces. In some embodiments, metal product 100 may be formed by employing continuous casting system 300.

[0047] Continuous casting system 300 illustrated in FIG 3 may have a pair of opposed casting surfaces 340 and 342 configured to move such that metal advances through the casting surfaces 340 and 342 in casting direction 390. Casting direction 390 may correspond to the direction that casting surfaces 340 and 342 are moving or are configured to move to a metal product while casting. Casting surfaces 340 and 342 may oppose each other, such that each casting surface may be configured to move in a direction that directly mirrors that of the opposite casting surface. For example, casting surface 340 may be configured to move or rotate towards casting surface 342, and casting surface 342 may be configured to move or rotate towards casting surface 340.

[0048] Casting surfaces 340 and 342 may comprise a variety of types of casting surfaces, such as casting rollers, belts, conveyors, or blocks. In various embodiments, casting surfaces 340 and 342 may be different from each other. For example, casting surface 340 may be a casting roller while casting surface 342 may be a conveyor. In other embodiments, both casting surface 340 and casting surface 342 may be the same type of casting surfaces. For example, as illustrated in FIG. 3, both casting surface 340 and casting surface 342 may be casting rollers.

[0049] In various embodiments, a plurality of casting surfaces 340 and 342 may be employed in continuous casting system 300. For example, casting surfaces 340 and 342 and additional casting surfaces (not shown in FIG. 3) may be employed during the continuous casting of a metal product. In other embodiments, more than four casting surfaces may be employed in continuous casting system 300. As a few non-limiting examples, continuous casting system 300 may have a 4-casting surface configuration, an 8-casting surface configuration, or a 12-casting surface configuration. A belt-like or conveyor-like casting surface may also be used.

[0050] Casting cavity 360 may exist between the pair of opposed casting surfaces 340 and 342. Casting cavity 360 may be the region between the pair of opposing casting surfaces 340 and 342 into which molten metal alloys are delivered for processing. Continuous casting system 300 may have a plurality of molten metal injectors, such as, injectors 312, 314, and 316. As used herein the phrase "molten metal injectors" is interchangeable and coextensive with metal injectors or injectors. Each injector may be configured for and correspond to an independent metal alloy source. In various embodiments, each injector 312, 314, and 316 may correspond to a different metal alloy source. For example, injector 312 may correspond to a first 5xxx series aluminum alloy source, injector 314 may correspond to a second 5xxx series aluminum alloy source, and injector 316 may correspond to a third 5xxx series aluminum alloy source. In other embodiments, the metal alloys provided by directly adjacent injectors may be different from each other. In other words, the metal alloy for injectors 312 and 316 may be different than the metal alloy corresponding to injector 314. In some examples, the metal alloy corresponding to injector 312 may be the same metal alloy corresponding to injector 316, although it need not. For example, the same 5xxx series aluminum alloy may correspond to both injector 312 and injector 316, but a different 5xxx series (or other series) aluminum alloy may correspond to injector 314. Accordingly, the metal alloys provided by directly adjacent injectors, such as 312 and 314 or 314 and 316, may correspond to different metal alloys.

[0051] Molten metal injectors 312, 314, and 316 may each have an end opening (not shown in FIG. 3). The end opening may be positioned on the ends of injectors 312, 314, and 316 proximate to casting cavity 360. Each end opening of injectors 312, 314, and 316 may be configured to inject a molten metal alloy from each of injectors 312, 314, and 316 into casting cavity 360. Injectors 312, 314, and 316 may be configured to inject molten metal alloys into casting cavity 360 in the direction of casting direction 390. Positions of ends of the different injectors may be varied along casting direction 390, such as to allow certain alloys more or less time in contact with the casting surfaces 340 and 342 to allow for partial solidification. Separators or partition elements may be positioned between different injectors to prevent the molten metals from contacting one another for a period of time, such as until at least one of the molten metals becomes at least partially solid.

[0052] As illustrated in FIG. 3, injectors 312, 314, and 316 may be distributed consecutively adjacent to each other. For example, injector 312 may be arranged directly adjacent to injector 314, and injector 314 may be arranged directly adjacent to injector 316. Similar to the discussion above with regards to layers 112, 114, and 116 and layers 212, 214, and 216, the phrase "directly adjacent" implies that injectors 312, 314, and 316 may be proximate to each other. The distribution of injectors 312, 314, and 316 may also be linear such that each injector is distributed consecutively in the same plane or along a common axis. Injectors 312, 314, and 316 may be distributed consecutively in a plane perpendicular to casting direction 390, as shown in FIG. 3.

[0053] For example, injectors 312, 314, and 316 may be distributed perpendicular to casting direction 390 along the length of casting surfaces 340 and 342. As illustrated in FIG. 3, injectors 312, 314, and 316 may be distributed consecutively in a manner parallel to casting cavity 360. In various embodiments, the illustrated arrangement of injectors 312, 314, and 316 may correspond to that used for casting metal product 100 by continuous casting system 300. Each injector 312, 314, and 316 of continuous casting system 300 may each correspond to an independent layer of metal alloy in metal product 100. For example, injector 312 may correspond to layer 112 comprising metal alloy 102, injector 314 may correspond to layer 114 comprising metal alloy 104, and injector 316 may correspond to layer 116 comprising metal alloy 106 in metal product 100. The distribution of injectors 312, 314, and 316 may correspond to the distribution of layers 112, 114, and 116 comprising metal product 100.

[0054] In some embodiments, the width of casting surfaces 340 and 342 may range from about 0.1 m to about 10 m, such as from 0.1 m to 1 m, from 1 m to 2 m, from 2 m to 3 m, from 3 m to 5 m, or from 5 m to 10 m. In other embodiments, the width of casting surfaces 340 and 342 may range from 0.1 m to 0.2 m, from 0.2 m to 0.3 m, from 0.3 m to 0.4 m, or from 0.4 m to 0.5

m. In some embodiments, injectors 312, 314, and 316 may extend the entire width of casting surfaces 340 and 342. However, in other embodiments, injectors 312, 314, and 316 may only extend a portion of the entire width of casting surfaces 340 and 342. For example, injectors 312, 314, and 316 may be distributed only along the middle (for example, 1 m of an entire 2 m width) of casting surfaces 340 and 342, leaving about exposed casting surface (e.g., 0.5 m exposed) on either side of the distribution of injectors 312, 314, and 316.

[0055] While only three injectors 312, 314, and 316 are illustrated in FIG. 3, in various embodiments the number of injectors may be more than three. For example, the number of injectors may optionally range from 3 to 50 or even more than 50. In embodiments, the number of injectors employed to continuous cast a metal product may be from 3 to 50, from 5 to 50, from 10 to 50, from 15 to 50, from 20 to 50, from 25 to 50, from 30 to 50, from 35 to 50, from 40 to 50, from 45 to 50, from 3 to 45, from 5 to 45, from 10 to 45, from 15 to 45, from 20 to 45, from 25 to 45, from 30 to 45, from 35 to 45, from 40 to 45, from 3 to 40, from 5 to 40, from 10 to 40, from 15 to 40, from 20 to 40, from 25 to 40, from 30 to 40, from 35 to 40, from 3 to 35, from 5 to 35, from 10 to 35, from 15 to 35, from 20 to 35, from 25 to 35, from 30 to 35, from 3 to 25, from 5 to 25, from 10 to 25, from 15 to 25, from 20 to 25, from 3 to 20, from 5 to 20, from 10 to 20, from 15 to 20, from 3 to 15, from 5 to 15, from 10 to 15, from 3 to 10, from 5 to 10, or from 3 to 5.

[0056] Continuous casting system 300 may further include a heat removal system. A heat removal system may be beneficial for controlling the solidification rate and solidification process for the molten metal alloys. An exemplary heat removal system may be a heat removal system that is positioned within the casting rollers and designed to cool casting surfaces 340 and 342. When such a heat removal system is employed, the heat removal system may be configured to provide different amounts of cooling at various points along the width of casting surfaces 340 and 342. Because metal alloy 302, 304, and 306 may be different from each other, the metal alloys may have different phase transition profiles, such as solidus or melting temperatures. Thus, to provide tailored and optimal heat removal to each of the metal alloys, the cooling rate supplied by the heat removal system within the casters may vary along the width of casting surfaces 340 and 342. The amount of cooling provided by the heat removal system may depend on the metal alloy and a desired rate of cooling/solidification. Controlling the rate of solidification may optionally impact formation of a final product, such as the near-surface microstructure formed during solidification.

[0057] Although FIG. 3 is depicted with a vertical casting configuration, such as where casting direction 390 is in a vertical direction, it will be appreciated that other casting configurations may also or alternatively be employed, such as a horizontal casting configuration where casting surfaces 340 and 342 are arranged in a horizontal casting direction, for example where the casting direction 390 is horizontal. Use of a horizontal casting configuration may be advantageous for embodiments where the metal product is subjected to one or more hot rolling or cold rolling passes.

[0058] FIG. 4 provides a schematic illustration of continuous casting system 400 having three injectors consecutively distributed between the opposed casting surfaces. FIG. 4 illustrates an example arrangement of injectors and casting surfaces for continuous casting a metal product. The metal product may optionally correspond to metal product 200. For example, FIG. 4 may illustrate the distribution of injectors 412, 414, and 416 and casting surfaces 440 and 442 of continuous casting system 400 employed for forming metal product 200.

[0059] Continuous casting system 400 may have a pair of opposed casting surfaces 440 and 442 configured so they advance metal product in casting direction 490. As noted above, casting surfaces, such as 440 and 442, may be opposed such that they move or rotate in a direction that directly mirrors each other. For example, as depicted in FIG. 4, casting surface 440 is configured to rotate towards casting surface 442, while casting surface 442 is configured to rotate towards casting surface 440. Casting direction 490 may correspond to a direction that a metal product, such as, metal product 200, may move through casting surfaces 440 and 442 during the casting process.

[0060] Casting surfaces 440 and 442 may comprise a variety of casters. For example, casting surfaces 440 and 442 may be casting rollers, belts, conveyors, or blocks. In various embodiments, casting surface 440 may be a different type of caster than casting surface 442. For example, casting surface 440 may be a casting roller and casting surface 442 may be a conveyor type caster. In other embodiments, both casting surface 440 and casting surface 442 may be the same type of caster. For example, as illustrated in FIG. 4, both casting surfaces 440 and 442 may be casting rollers.

[0061] In various embodiments, a plurality of casting surfaces 440 and 442 may be employed in continuous casting system 400. For example, subsequent to casting surfaces 440 and 442, continuous casting system 400, additional casting surfaces (not shown) may be employed. Optionally, more than four casting surfaces may be employed during the continuous casting of a metal product. For example, continuous casting system 400 may employ a 4-casting surface configuration, an 8-casting surface configuration, or a 12-casting surface configuration.

[0062] Casting cavity 460 may exist between the pair of opposed casting surfaces 440 and 442. Casting cavity 460 may be the area between casting surfaces 440 and 442 that molten metal alloys are injected into for processing in continuous casting system 400. Casting cavity 460 may extend along the length of casting surfaces 440 and 442 and may include the region between casting surfaces 440 and 442 that defines a separation distance between the two casting surfaces.

[0063] As illustrated in FIG. 4, continuous casting system 400 may have a plurality of molten metal injectors, such as injectors 412, 414, and 416. Injectors 412, 414, and 416 may be configured to inject molten metal alloys into casting cavity 460. Each injector may be configured for providing, and may correspond to, an independent metal alloy. In various embodiments, at least one injector 412, 414, and 416 may correspond to a different metal alloy from another injector. For example, injector 412 may correspond to a first 5xxx series aluminum alloy, injector 414 may correspond to a second 5xxx series aluminum alloy, and injector 416 may correspond to a third 5xxx series aluminum alloy. In other embodiments, the metal alloys of directly adjacent injectors, such as injectors 412 and 414 or injectors 414 and 416, may be different from each other while the metal alloy corresponding to injector 412 may be the same metal alloy as the metal alloy corresponding to injector 416. For example, the same 5xxx series aluminum alloy may correspond to both injector 412 and injector 416, but a different 5xxx series (or other series) aluminum alloy may correspond to injector 414. In embodiments, the metal alloys corresponding to directly adjacent injectors may not be the same metal alloy.

[0064] Molten metal injectors 412, 414, and 416 may each have an end opening. The end opening may be positioned on the ends of injectors 412, 414, and 416 proximate to casting cavity 460. Each end opening of injectors 412, 414, and 416 may be configured to inject a molten metal alloy from injectors 412, 414, and 416 into casting cavity 460. Injectors 412, 414, and 416 may be configured to inject the molten metal alloys in casting direction 490 into casting cavity 460. Each end opening may be independently positioned along casting direction 490 to allow more or less time for cooling of an injected molten alloy before coming into contact with other alloys.

[0065] Injectors 412, 414, and 416 of continuous casting system 400 may be distributed consecutively adjacent to each other. For example, injector 412 may be distributed directly adjacent to injector 414, and injector 414 may be distributed directly adjacent to injector 416. As noted in the discussion regarding FIG. 3, the phrase “directly adjacent” indicates that injectors 412 and 414 or 414 and 416 may be proximate to each other such that emitted alloys may come into direct contact with one another. Injectors 412, 414, and 416 may be distributed linearly with respect to each other such that each injector is distributed consecutively in the same plane. Injectors 412, 414, and 416 may be distributed consecutively in a plane perpendicular to casting direction 490, as shown in FIG. 4.

[0066] Optionally, injectors 412, 414, and 416 may be distributed perpendicular to casting direction 490 along an axis parallel to the separation between casting surfaces 440 and 442 (i.e., parallel to the thickness dimension in the resultant cast product). As illustrated in FIG. 4, injectors 412, 414, and 416 may be distributed consecutively perpendicular to casting cavity 460 such that the distribution extends along the separation distance between casting surfaces 440 and 442. The separation distance between casting surfaces 440 and 442 may correspond to the minimum distance between casting surfaces 440 and 442. It will be appreciated that the separation distance between casting surfaces 440 and 442 may correspond to a thickness or approximate thickness of a metal product processed by continuous casting system 400. For example, the thickness of metal product 200 processed by continuous casting system 400 may correspond to the separation width of casting surfaces 440 and 442.

[0067] In some embodiments, injectors 412, 414, and 416 in the arrangement illustrated may be used to cast metal product 200 using continuous casting system 400. In such embodiments, injectors 412, 414, and 416 may each correspond to an independent layer of metal alloy in metal product 200. For example, injector 412 may correspond to layer 212 comprising metal alloy 202, injector 414 may correspond to layer 214 comprising metal alloy 204, and injector 416 may correspond to layer 216 comprising metal alloy 206. As explained above, at least one of metal alloy 202, 204 and 206 may be different from another of metal alloy 202, 204, and 206.

[0068] As noted above, the thickness of a metal product, such as the thickness of metal product 200, may correspond to the separation distance between casting surfaces 440 and 442.

In some embodiments, the separation distance between casting surfaces 440 and 442 may optionally range from 1 mm to about 100 mm, such as from 1 mm to 4 mm, from 4 mm to 8 mm, from 8 mm to 15 mm, from 15 mm to 20 mm, from 20 mm to 30 mm, from 30 mm to 50 mm, or from 50 mm to 100 mm. In other embodiments, the separation width may be greater than 100 mm, depending on the metal product and configuration of the continuous casting system 400.

[0069] In various embodiments, the number of injectors employed in continuous casting system 400 may be more than three. For example, the number of injectors employed by continuous casting system 400 may optionally range from 3 to 50, or even more than 50. In other embodiments, the number of injectors employed in continuous casting system 400 may range from 3 to 50, from 5 to 50, from 10 to 50, from 15 to 50, from 20 to 50, from 25 to 50, from 30 to 50, from 35 to 50, from 40 to 50, from 45 to 50, from 3 to 45, from 5 to 45, from 10 to 45, from 15 to 45, from 20 to 45, from 25 to 45, from 30 to 45, from 35 to 45, from 40 to 45, from 3 to 40, from 5 to 40, from 10 to 40, from 15 to 40, from 20 to 40, from 25 to 40, from 30 to 40, from 35 to 40, from 3 to 35, from 5 to 35, from 10 to 35, from 15 to 35, from 20 to 35, from 25 to 35, from 30 to 35, from 3 to 25, from 5 to 25, from 10 to 25, from 15 to 25, from 20 to 25, from 3 to 20, from 5 to 20, from 10 to 20, from 15 to 20, from 3 to 15, from 5 to 15, from 10 to 15, from 3 to 10, from 5 to 10, or from 3 to 5.

[0070] Continuous casting system 400 may further include a heat removal system. A heat removal system may be beneficial for controlling the solidification rate and process for the molten metal alloys. An exemplary heat removal system may be a heat removal system that is positioned within the casting rollers and designed to cool casting surfaces 440 and 442. Because metal alloy 402, 404, and 406 may be different from each other, and thus have different solidification rates, the cooling rate supplied to each casting surface may be different from the other. That is, if metal alloy 402 requires a faster rate of cooling than metal alloy 406, then casting surface 440 may be maintained at a lower temperature than casting surface 442, for example. Because metal alloy 404 may not contact either of casting surfaces 440 and 442, heat removal for metal alloy 404 may be achieved by another means. For example, a cooling element may be positioned to contact the metal alloy 404 as the metal alloy is injected from injector 414. Such cooling elements are discussed in greater detail with respect to FIG. 5. As noted above, controlling the rate of solidification may impact the formation of a final product, such as the near-surface microstructure. Thus, the amount of cooling provided by the heat removal system may depend on the metal alloy and a desired rate of cooling/solidification.

[0071] Although FIG. 4 is depicted with a vertical casting configuration, such as where casting direction 490 is a vertical direction, it will be appreciated that other casting configurations may also or alternatively be employed, such as a horizontal casting configuration where casting surfaces 440 and 442 are arranged in a horizontal casting direction, for example where casting direction 490 is horizontal.

[0072] FIG. 5 illustrates a cross-sectional schematic of continuous casting system 500. Continuous casting system 500 may optionally be the same as continuous casting system 400. Continuous casting system 500 may have a pair of opposed casting surfaces 540 and 542. Casting surfaces 540 and 542 may be configured to advance metal product in casting direction 590. If roll casters are used, casting surfaces 540 and 542 may be configured to rotate in mirrored directions. For example, as indicated on FIG. 5, casting surface 540 may be configured to rotate towards casting surface 542, and casting surface 542 may be configured to rotate towards casting surface 540. As discussed above, casting surfaces 540 and 542 may have a separation distance. Separation distance 545 illustrates the distance between casting surfaces 540 and 542 that may define a thickness of a cast product, for example.

[0073] Continuous casting system 500 may have three metal injectors 512, 514, and 516. Injectors 512, 514, and 516 may be the same as injectors 412, 414, and 416, although they need not be. As discussed with respect to injectors 412, 414, and 416, injectors 512, 514, and 516 may be distributed perpendicular to casting direction 590 along separation distance 545. Injectors 512, 514, and 516 may be consecutively distributed in a linear fashion such that, for example, injector 512 is directly adjacent to injector 514, and injector 514 is directly adjacent to 516. All three injectors 512, 514, and 516 may optionally be distributed in the same plane.

[0074] Injectors 512, 514, and 516 may be configured to inject molten metal alloys into casting cavity 560. As illustrated in FIG. 5, injector 512 may inject metal alloy 502, injector 514 may inject metal alloy 504, and injector 516 may inject metal alloy 506 into casting cavity 560. In various embodiments, metal alloys 502, 504, and 506 may be the same as metal alloys 402, 404, and 406, respectively, or the same as metal alloys 202, 204, and 206, respectively, or the same metal alloys 102, 104 and 106, respectively.

[0075] In some embodiments, continuous casting system 500 may correspond to metal product 200 processed by continuous casting system 500. In these embodiments, each injector 512, 514, and 516 may correspond to a layer of metal alloy of metal product 200. For example, injector 512 may be configured to inject metal alloy 202 in a molten state, injector 514 may be configured to inject metal alloy 204 in a molten state, and injector 516 may be configured to inject metal alloy 206 in a molten state. After casting, metal product 200 may be formed such that injector 512 corresponds to layer 212 comprising metal alloy 202, injector 514 corresponds to layer 214 comprising metal alloy 204, and injector 516 corresponds to layer 216 comprising metal alloy 206.

[0076] Optionally, continuous casting system 500 may have one or more partitioning devices 550 and 552. As illustrated in FIG. 5, partitioning devices 550 and 552 may be positioned between directly adjacent injectors. For example, partitioning device 550 may be positioned between directly adjacent injectors 512 and 514, and partitioning device 552 may be positioned between directly adjacent injectors 514 and 516. In various embodiments, partitioning devices 550 and 552 may be positioned only between two directly adjacent injectors and leave any remaining directly adjacent injectors without a partitioning device between them. For example, partitioning device 550 may be positioned between injector 512 and directly adjacent injector 514 while no partitioning device 552 is positioned between injector 514 and directly adjacent injector 516. Instead, injector 514 and injector 516 may be positioned proximate to each other with no partitioning device between them.

[0077] Partitioning devices 550 and 552 may be manufactured from a material that can withstand the high temperatures and characteristics of molten metal alloys. The material may be a refractory or a coated refractory material. In various embodiments, partitioning devices 550 and 552 may be manufactured in part from molybdenum, tungsten, tantalum, or rhenium. In other embodiments, partitioning devices 550 and 552 may be manufactured in part or in whole from titanium, zirconium, hafnium, rutherfordium, vanadium, niobium, dubnium, chromium, seaborgium, manganese, technetium, or bohrium.

[0078] Partitioning devices 550 and 552 may extend the entire width of injectors 512, 514, and 516. Partitioning devices 550 and 552 may partition injected molten metal alloys from each of injectors 512, 514, and 516 such that the molten metal alloys are partitioned until they reach a certain depth into casting cavity 560. As illustrated in FIG. 5, partitioning devices 550 may partition injected metal alloy 502 via injector 512 from injected metal alloy 504 via injector 514 and partitioning device 552 may partition injected metal alloy 504 via injector 514 from injected metal alloy 506 via injector 516. Depending on the length of partitioning devices 550 and 552, partitioning devices 550 and 552 may partition directly adjacent metal alloys to a certain depth into casting cavity 560. As illustrated in FIG. 5, partitioning devices 550 and 552 may extend beyond the end of the directly adjacent injectors. For example, partitioning device 550 may extend beyond the ends of injectors 512 and 514 into casting cavity 560, and partitioning device 552 may extend beyond the ends of injectors 514 and 516 into casting cavity 560.

[0079] By partitioning directly adjacent molten metal alloys as they are injected from injectors 512, 514, and 516 into casting cavity 560, at least one of a pair of directly adjacent metal alloys may be cooled before coming in contact with each other. Without wishing to be bound by any theory, it is believed that allowing a metal alloy to cool, even slightly, before contacting a directly adjacent metal alloy may reduce the amount of diffusion that occurs at the interface of the two directly adjacent metal alloys. Cooling the interfaces of a molten metal alloy allows the molten metal alloy at the interface surface to begin to solidify, rendering the metal alloy at the interface surface into a semi- or partially solidified molten state.

[0080] In some embodiments, partitioning devices 550 and 552 may be tapered or blade-like such as coming to a pinnacle or point at an end proximate to the casting cavity 560. Providing a tapered end to partitioning devices 550 and 552 may be advantageous to minimize mixing or blending of metal alloys 502, 504, and 506 as they are injected into casting cavity 560 in a molten state. Tapering the ends of partitioning devices 550 and 552 proximate to casting cavity 560 may reduce turbulence and/or a pressure differential between adjacent metal alloys as the metal alloys are injected, such as metal alloy 504 and metal alloy 506. Reducing turbulence and/or a pressure differential between adjacent metal alloys may reduce mixing and diffusion between the two adjacent metal alloys. Mixing between adjacent metal alloys may also be reduced by allowing partial solidification of one or more of the metal alloys before coming in contact with an adjacent metal alloy. For example, by partitioning metal alloy 506 from metal alloy 504, metal alloy 506 may at least partially solidify before contacting metal alloy 504. If metal alloy 506 is at least partially solidified, then mixing or blending between metal alloy 504 and metal alloy 506 may be reduced, such as when compared to a condition where metal alloy 506 is completely molten. Metal alloy 506 may be partially solidified before contacting metal alloy 504 due to the use of heat removal systems incorporated into the casting system. For example, a heat removal system may be incorporated within the casting system such that casting surfaces 540 and 542 maintain a particular temperature to partially solidify metal alloy 506 and/or metal alloy 502 when metal alloys 506 and 502 contact the casting surfaces 540 and 542, respectively. In embodiments, one or more of the metal alloys may be completely solidified when contacted by an adjacent metal alloy. To achieve metallurgical bonding between the adjacent metal alloys, for example, the heat of a non-solidified metal alloy or pressure generated within the casting cavity between the adjacent metal alloys may partially melt a contacting surface of the completely solidified metal alloy, allowing for metallurgical bonding to occur between the adjacent metal alloys.

[0081] Partitioning devices 550 and 552 may also provide for partial solidification of one or more of metal alloys 502, 504, and 506. Partitioning devices 550 and 552 may include elements 554 and 556, respectively. Elements 554 and 556 may be heating elements used to elevate the temperature of the molten metal alloys as they are injected from injectors 512, 514, and 516 into casting cavity 560. By elevating the temperature of the interface surfaces of metal alloys, continuous bonding between adjacent interfaces may be achieved. Optionally, in embodiments, elements 554 and 556 may be or represent cooling elements used to lower the temperature of the molten metal alloys as they are injected to provide for partial solidification. The continuous bonding may be metallurgical bonding between the two directly adjacent metal alloys.

[0082] In embodiments where elements 554 and 556 are cooling elements, elements 554 and 556 may drop the surface temperature of the molten metal alloys as they are injected from injectors 512, 514, and 516 into casting cavity 560. By dropping the temperature of the interface surfaces of the metal alloys, a metal alloy at or near the interface surface may fall below a liquidus temperature, for example, such that the metal alloy may be in a partially solid state. This may allow for formation of distinct layers of metal alloy in a metal product by minimizing diffusion between two directly adjacent metal alloys, or with smaller diffusion zones than when fully molten alloys contact one another. Additionally, by lowering the temperature of the interface surfaces of metal alloys, controlled bonding between adjacent interfaces may be achieved. In applications where minimal diffusion or controlled diffusion is desirable, elements 554 and 556 may control the solidification of one or more of the metal alloys to achieve a controlled level of diffusion and bonding between adjacent metal alloys.

[0083] As illustrated in FIG. 5, partitioning devices 550 and 552 may partition metal alloys 502, 504, and 506 when they are injected from injectors 512, 514, and 516 into casting cavity 560. Optionally, depending on the conditions during the injection process, partitioning devices 550 and 552 may cause partitioning of metal alloys 502, 504, and 506 beyond the end of partitioning devices 550 and 552. As discussed above, in some embodiments, if the interface surfaces of directly adjacent metal alloys are cooled by elements 554 and 556 and begin to solidify, then distinct interfaces between metal alloys 502, 504, and 506 may form. This may result in partitioning of metal alloys 502, 504, and 506 beyond the end of partitioning devices 550 and 552 and well into casting cavity 560. Partitioning of metal alloys beyond the ends of partitioning devices 550 and 552 may limit diffusion between directly adjacent metal alloys. Accordingly, partitioning devices 550 and 552 may be configured to control the degree of mixing and diffusion between directly adjacent metal alloys during the injection and bonding phases of the continuous casting process. In various embodiments, a composite substrate formed from metal alloys 502, 504, and 506 by casting surfaces 540 and 542, may exit continuous casting system 500 in a completely solidified state. That is, when the composite substrate is beyond point 545, the composite substrate, formed from metal alloys 502, 504, and 506 may be completely solidified. However, in other embodiments, the composite substrate may only be partially solidified beyond point 545 as the composite substrate exits continuous casting system 500.

[0084] Although FIG. 5 is depicted with a vertical casting configuration, such as where casting direction 590 is in a vertical direction, it will be appreciated that other casting configurations may also or alternatively be employed, such as a horizontal casting configuration where casting surfaces 540 and 542 are arranged in a horizontal casting direction, for example where casting direction 590 is horizontal.

[0085] FIG. 6 provides a schematic overview of continuous casting system 600. Continuous casting system 600 may be the same as continuous casting system 500, continuous casting system 400, or continuous casting system 300. Continuous casting system 600 may have a pair of opposed casting surfaces 640 and 642. Casting surfaces 640 and 642 may advance metal in casting direction 690. Casting surfaces 640 and 642 may rotate in a direction that directly mirrors each other. For example, as depicted in FIG. 6, casting surface 640 may rotate towards casting surface 642, and casting surface 642 may rotate towards casting surface 640. Optionally, continuous casting system 600 may further include one or more rolling stands (not shown) positioned to receive a composite substrate from the at least one pair of moving opposed casting surfaces 640 and 642.

[0086] As noted above, casting surfaces 640 and 642 may be a variety of casters. For example, casting surfaces 640 and 642 may be rolling casters, conveyers, belts, or blocks. In some embodiments, casting surfaces 640 and 642 may be different types of casters from each other. For example, casting surface 640 may be a conveyor while casting surface 642 may be a rolling caster. In other embodiments, casting surfaces 640 and 642 may comprise the same type of caster. For example, casting surfaces 640 and 642 may both be belt or conveyor type casters.

[0087] Optionally, casting surfaces 640 and 642 may employ one or more cooling systems 630. Cooling system 630 may cool the temperature of casting surfaces 640 and 642. Cooling system 630 may be incorporated into casting surfaces 640 and 642. In other embodiments, cooling system 630 may be external to casting surfaces 640 and 642 but still cool the temperature of casting surfaces 640 and 642.

[0088] As explained above, continuous casting system 600 may employ a plurality of molten metal injectors. The molten metal injectors employed by continuous casting system 600 may be injectors 612, 614, and 616. In various embodiments, the number of injectors employed by continuous casting system 600 may be more or less than three. For example, the number of injectors employed by continuous casting system 600 may optionally range from 3 to 5, 5 to 10, 10 to 20, or 20 to 50 injectors.

[0089] Injectors 612, 614, and 616 may be configured to inject molten metal alloys into a casting cavity. For example, injector 612 may be configured to inject metal alloy 602 in a molten phase, injector 614 may be configured to inject metal alloy 604 in a molten phase, and injector 616 may be configured to inject metal alloy 606 in a molten phase. All three injectors 612, 614, and 616 may be configured to inject their respective metal alloys into a casting cavity between casting surfaces 640 and 642. The casting cavity between casting surfaces 640 and 642 is not illustrated in FIG. 6 but may be similar to casting cavities 360, 460, or 560.

[0090] In various embodiments, continuous casting system 600 may employ a plurality of tundishes. The plurality of tundishes employed by continuous casting system 600 may include tundish 672, tundish 674, and tundish 676. Tundishes 672, 674, and 676 may be used to feed molten metal alloys, such as metal alloys 602, 604, and 606 in a molten phase, into injectors 612, 614, and 616. Tundishes 672, 674, and 676 may comprise, be lined with, or coated with a refractory compound. The refractory compound may be selected to be specific to the molten metal alloy respective to that tundish to minimize the amount of metal alloy build-up in the tundish. Tundishes 672, 674, and 676 may provide a reservoir of molten metal alloys to feed into injectors 612, 614, and 616 when upstream melting processes are inhibited.

[0091] Continuous casting system 600 may also employ a plurality of furnaces. The plurality of furnaces employed by continuous casting system 600 may be furnaces 682, 684, and 686. Molten metal alloys may be provided from furnaces 682, 684, and 686 to tundishes 672, 674, and 676, respectively. Molten metal alloys, such as metal alloys 602, 604, and 606, may undergo treatment while in furnaces 682, 684, and 686. Examples of treatments that metal alloys 602, 604, and 606 may experience while in furnaces 682, 684, and 686 may include degassing, alloying, or temperature correction treatments. Once metal alloys 602, 604, and 606 are in an appropriate state for processing, then furnaces 682, 684, and 686 may deliver metal alloys 602, 604, and 606 to tundishes 672, 674, and 676.

[0092] FIG. 7 provides an overview of a method 700 of continuously casting a metal product, as discussed above. Method 700 may be performed by employing a continuous casting system, such as for example, continuous casting system 300, continuous casting system 400, continuous casting system 500, or continuous casting system 600. Method 700 may be used to continuously cast a metal product, such as metal product 100 or metal product 200.

[0093] Method 700 may include providing a plurality of metal alloys into a casting cavity between a pair of moving opposed casting surfaces at block 710. The pair of moving opposed casting surfaces may be the same as casting surfaces 340 and 342, casting surfaces 440 and 442, casting surfaces 540 and 542, or casting surfaces 640 and 642, for example. In various embodiments, the pair of moving opposed casting surfaces may comprise two casting rollers or may be part of a conveyor type continuous casting system. The pair of moving opposed casting surfaces may move metal product in a casting direction. For example, a casting direction may be casting direction 390, casting direction 490, casting direction 590, or casting direction 690.

[0094] In various embodiments, providing a plurality of metal alloys may include providing at least three metal alloys, at least one of which is different from another of the alloys. In various embodiments, more than three metal alloys are provided into the casting cavity, as discussed above. The metal alloys may be simultaneously provided into the casting cavity, such that a plurality of metal alloys are providing throughout the duration of the continuous casting process. As discussed above, in some embodiments, the injection of a metal alloy may be interrupted to achieve a non-uniform layer distribution in a metal product. For example, a series of metal alloys may be provided simultaneously at the beginning of the continuous casting process, however, at a designated point in the casting process, the injection of at least one metal alloy of the series may be discontinued. This may form a non-uniform layer distribution in a metal product, such that the metal product comprises more or fewer layers at a starting end of the metal product than at a terminating end or center portion of the metal product.

[0095] Providing the metal alloys at block 710 may include injecting the metal alloys from a plurality of injectors at block 712. The plurality of injectors may correspond to the number of metal alloys being provided into the casting cavity. For example, if three metal alloys are provided into the casting cavity, then three injectors may be employed in the continuous casting system. Each injector may independently inject one of the plurality of metal alloys into the casting cavity. For example, a first injector may inject a first metal alloy, a second injector may inject a second metal alloy, and a third injector may inject a third metal alloy into the casting cavity. In some embodiments, the metal alloys of directly adjacent injectors may be different from each other. For example, if a first injector is directly adjacent to a second injector, and the second injector is directly adjacent to a third injector, then the metal alloy of the first injector may be different from the metal alloy of the second injector, and the metal alloy of the second injector may be different from the metal alloy of the third injector.

[0096] In various embodiments, the plurality of injectors may be distributed consecutively adjacent to one another in a direction perpendicular to the casting direction. Optionally, the plurality of injectors may be distributed along a width of the pair of moving opposed casting surfaces. For example, the plurality of injectors may be distributed as shown and described in FIG. 3. In other embodiments, the plurality of injectors may be distributed along a separation width of the pair of moving opposed casting surfaces. For example, the plurality of injectors may be distributed as shown and described in FIG. 4 or FIG. 5.

[0097] Optionally, providing a plurality of metal alloys may include partitioning the metal alloys from directly adjacent metal alloys at block 714. Partitioning the metal alloys may employ partitioning devices, such as, for example one or both of partitioning devices 550 and 552 as illustrated in FIG. 5. In various embodiments, partitioning devices used for partitioning the metal alloys may include use of heating elements or cooling elements. Heating elements or cooling elements employed at partitioning the metal alloys may control the temperature at the interfaces between directly adjacent metal alloys as they are injected from the plurality of injectors into the casting cavity.

[0098] Method 700 may also include cooling the metal alloys, at block 730, into a solid phase or semi-solid phase. Cooling the metal alloys may involve decreasing the temperature of the metal alloys. The temperature may decrease throughout the whole metal alloy or the temperature may decrease only at the interface surface of the metal alloys, at least initially. During cooling the metal alloys, interfaces may form between directly adjacent metal alloys. For example, interfaces may form between a first metal alloy and a second metal alloy at the surface interfaces of the first and second metal alloy proximate to each other. Metallurgical bonds may form at each interface. Cooling the metal alloys may optionally comprise cooling at least a portion of the pair of casting surfaces. For example, as illustrated in FIG. 6, cooling the metal alloys may comprise cooling casting surfaces 640 and 642 by employing cooling system 630. In various embodiments, cooling a portion of the casting surfaces may be achieved through an external cooling system.

[0099] Although FIG. 6 is depicted with a horizontal casting configuration, such as where casting direction 690 is in a horizontal direction, it will be appreciated that other casting configurations may also or alternatively be employed, such as a vertical casting configuration where casting surfaces 640 and 642 are arranged in a vertical casting direction, for example where casting direction 590 is vertical. Additionally, FIG. 6 is merely one example showing relative configuration of components to provide context for the casting process. The orientations, sizes, and arrangement of components depicted in FIG. 6 are for illustrative purposes and are not intended to be limiting.

[0100] Method 700 may include discharging a metal product 740. The metal product discharged at 740 may be metal product 100 or metal product 200, for example. The metal product discharged during method 700 may be a composite substrate with a length corresponding to the casting direction. In embodiments, the composite substrate may comprise a plurality of layers formed from the plurality of metal alloys provided into the casting cavity at block 710. The plurality of layers may correspond to the metal alloys metallurgically bonded together. In various embodiments, the plurality of layers extend along the casting direction and may be distributed perpendicular to the casting direction. In some embodiments, the plurality of layers may comprise at least three layers corresponding to at least three metal alloys.

[0101] In various embodiments, the plurality of layers may be distributed along a width of the composite substrate. For example, the plurality of layers may be distributed similar to the illustration in FIG. 1. As discussed above, the plurality of layers of metal product 100 are distributed such that layer 112 is directly adjacent to layer 114, and layer 114 is directly adjacent to layer 116, all three layers consecutively distributed perpendicular to the casting direction along the width of metal product 100. In other embodiments, method 700 may produce a composite having a plurality of layers distributed along a thickness of the composite substrate. Similar to the layer distribution illustrated and discussed with regards to FIG. 2, the plurality of layers may be consecutively distributed perpendicular to the casting direction along the thickness of the composite substrate.

[0102] Following casting, the cast product can be processed by any suitable means. Optionally, the processing steps can be used to prepare sheets, for example. Such processing/operation steps include, but are not limited to, homogenization, hot rolling, cold rolling, solution heat treatment, and an optional pre-aging step. Cast products can be processed and made products in the form of sheets, plates, or other suitable products.

EXAMPLE 1

[0103] A multi-alloy metal product is formed by continuous casting techniques, such as illustrated in FIG. 4. The metal product formed is metal product 200, illustrated in FIG. 2. Three metal alloys are simultaneously provided into a casting cavity of a pair of moving opposed casting surfaces. The three metal alloys are different from each other and include a first 5xxx series aluminum alloy, a second 5xxx series aluminum alloy, and a third 5xxx series aluminum alloy. The three metal alloys are injected into the casting cavity by three injectors. The injectors are configured to inject molten metal alloys and each injector injects one of the three metal alloys. The injectors are consecutively distributed perpendicular to the casting direction. The injectors are distributed perpendicular to the casting direction along the separation width of the casting surfaces. This arrangement of injectors forms the metal alloys into layers in a composite substrate that are distributed along the thickness of the composite substrate. The formed composite substrate is a metal plate having a thickness of 16 mm.

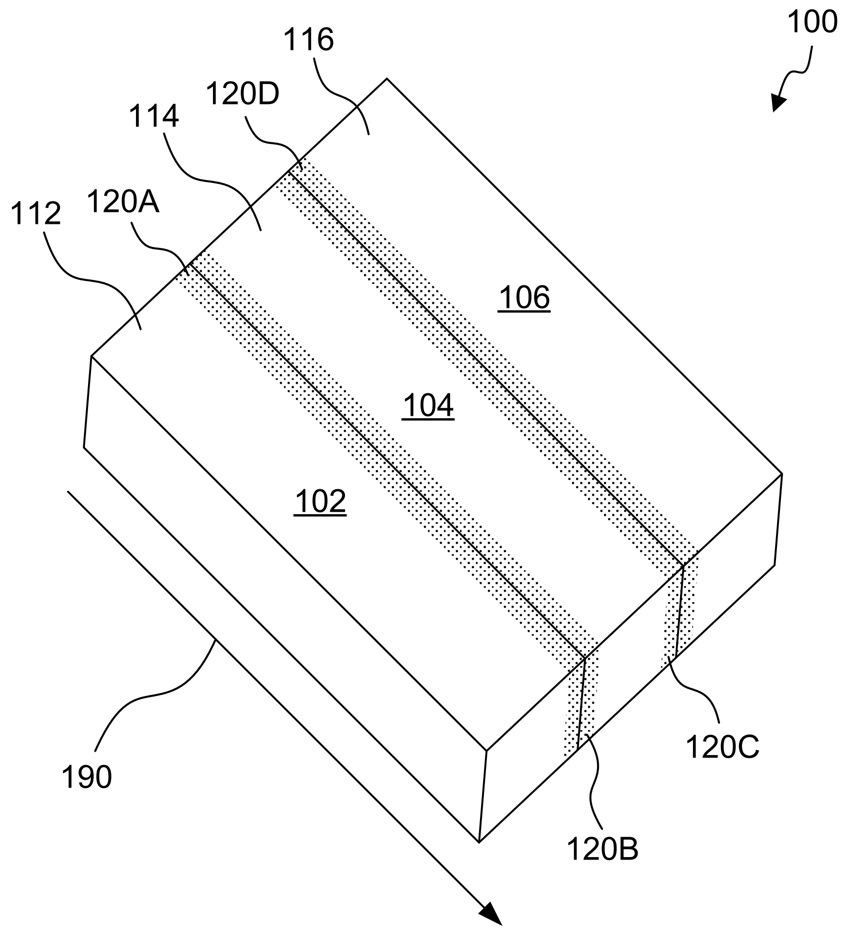

Figure 1

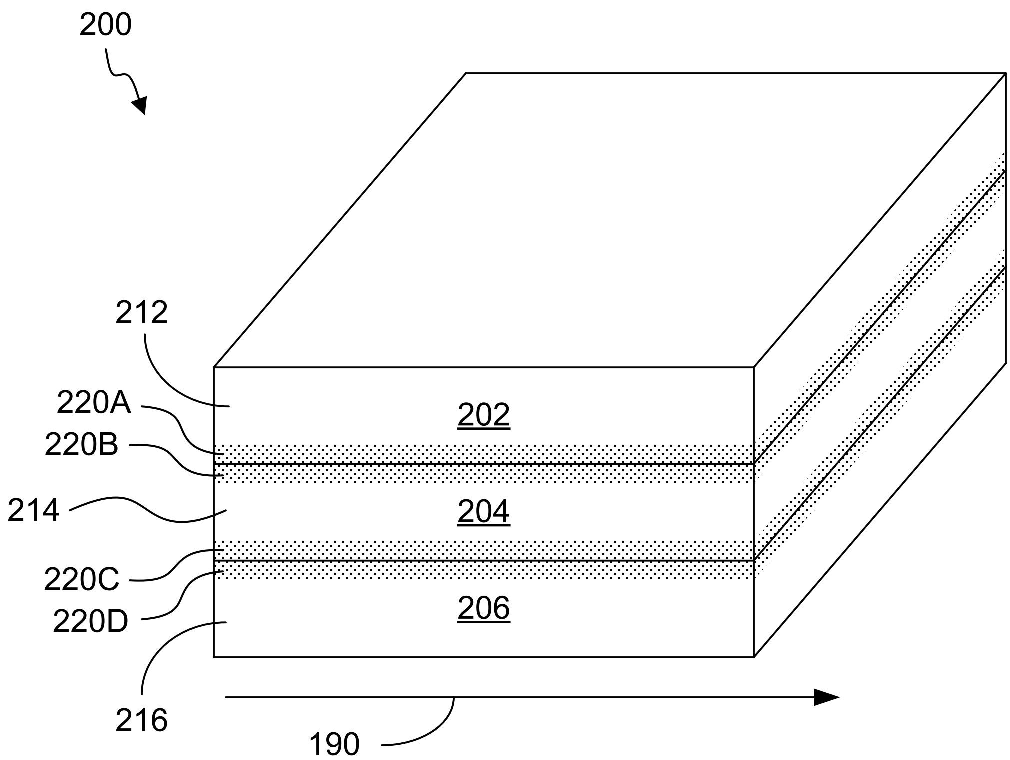

Figure 2

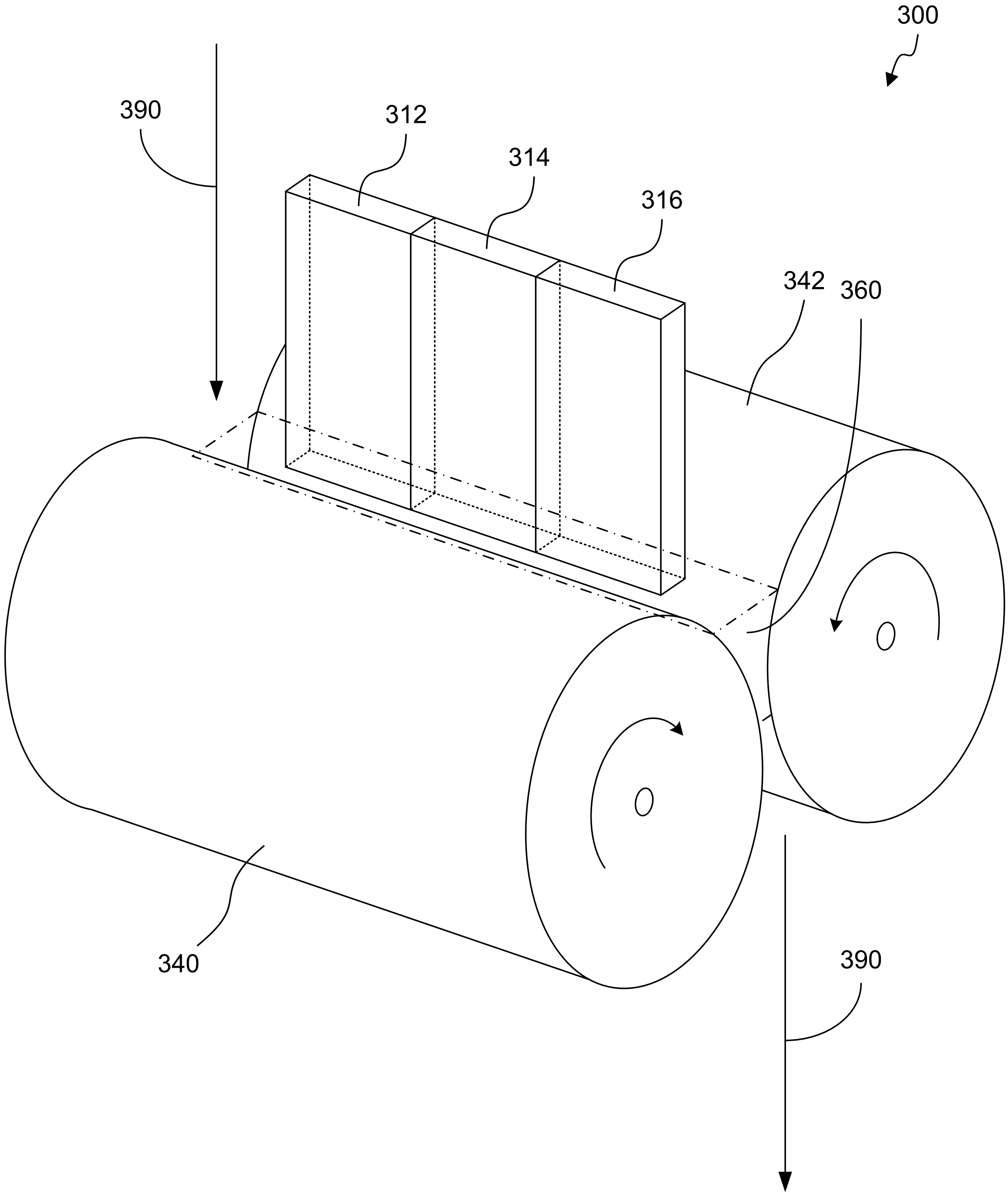

Figure 3

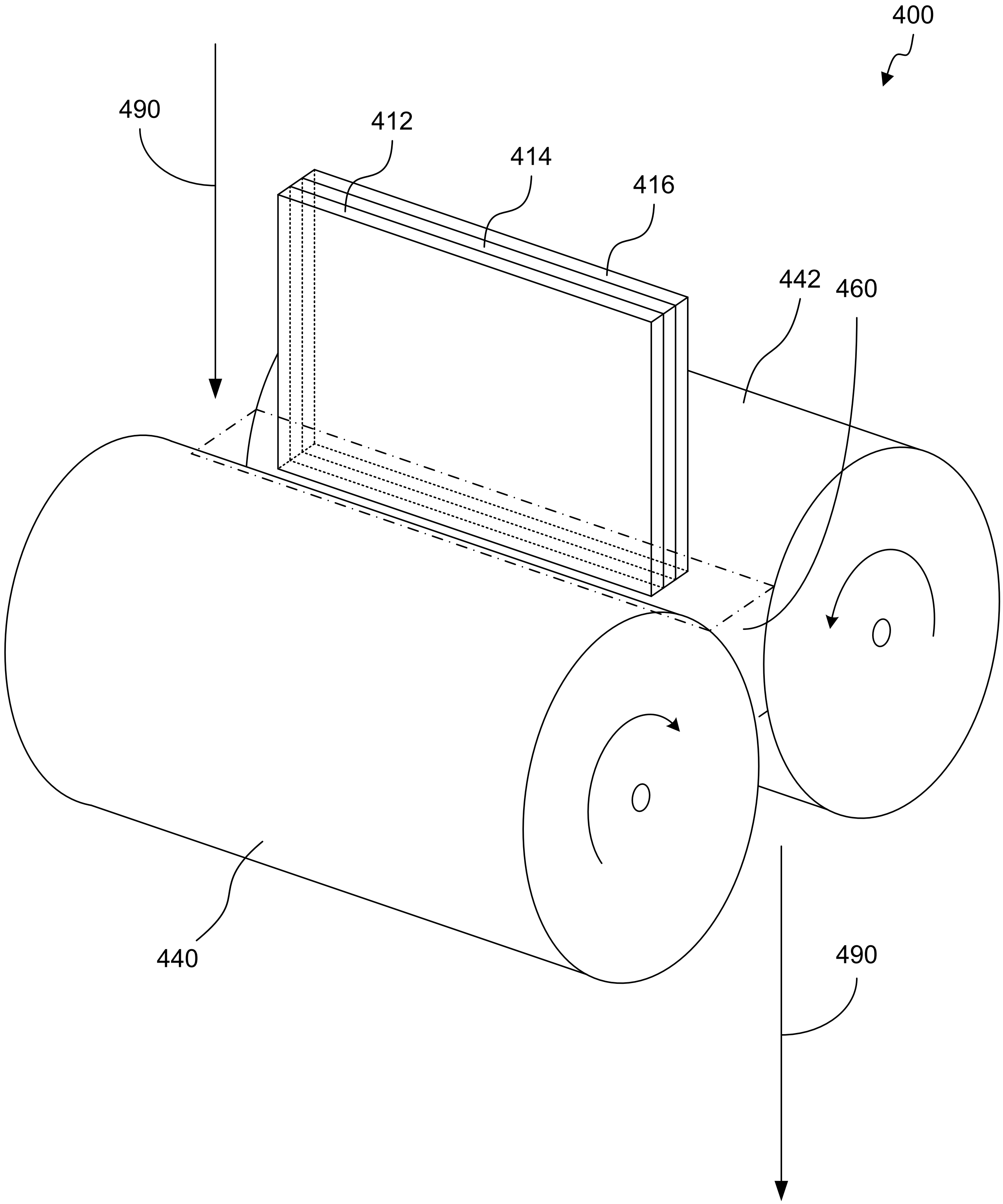

Figure 4

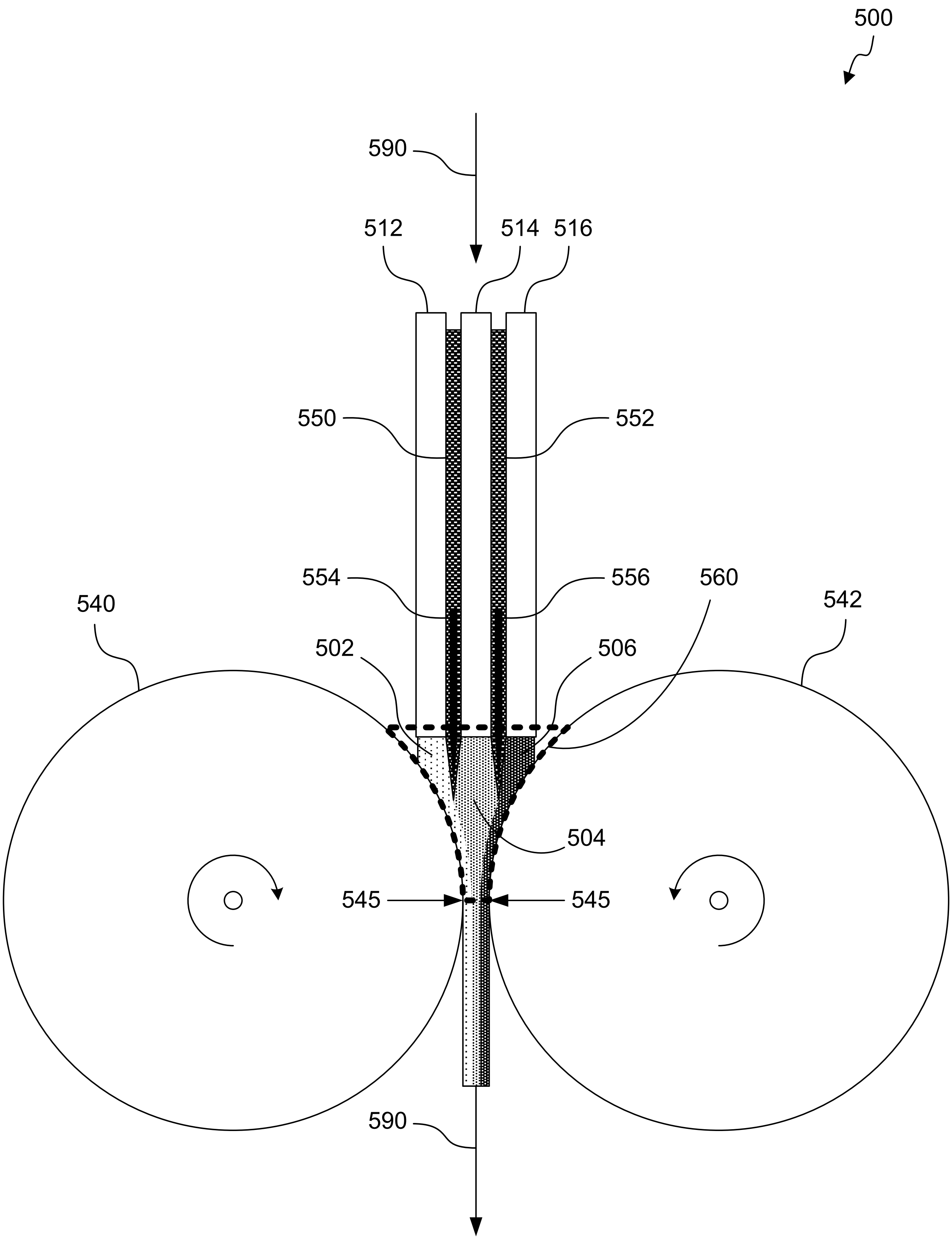
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Figure 5

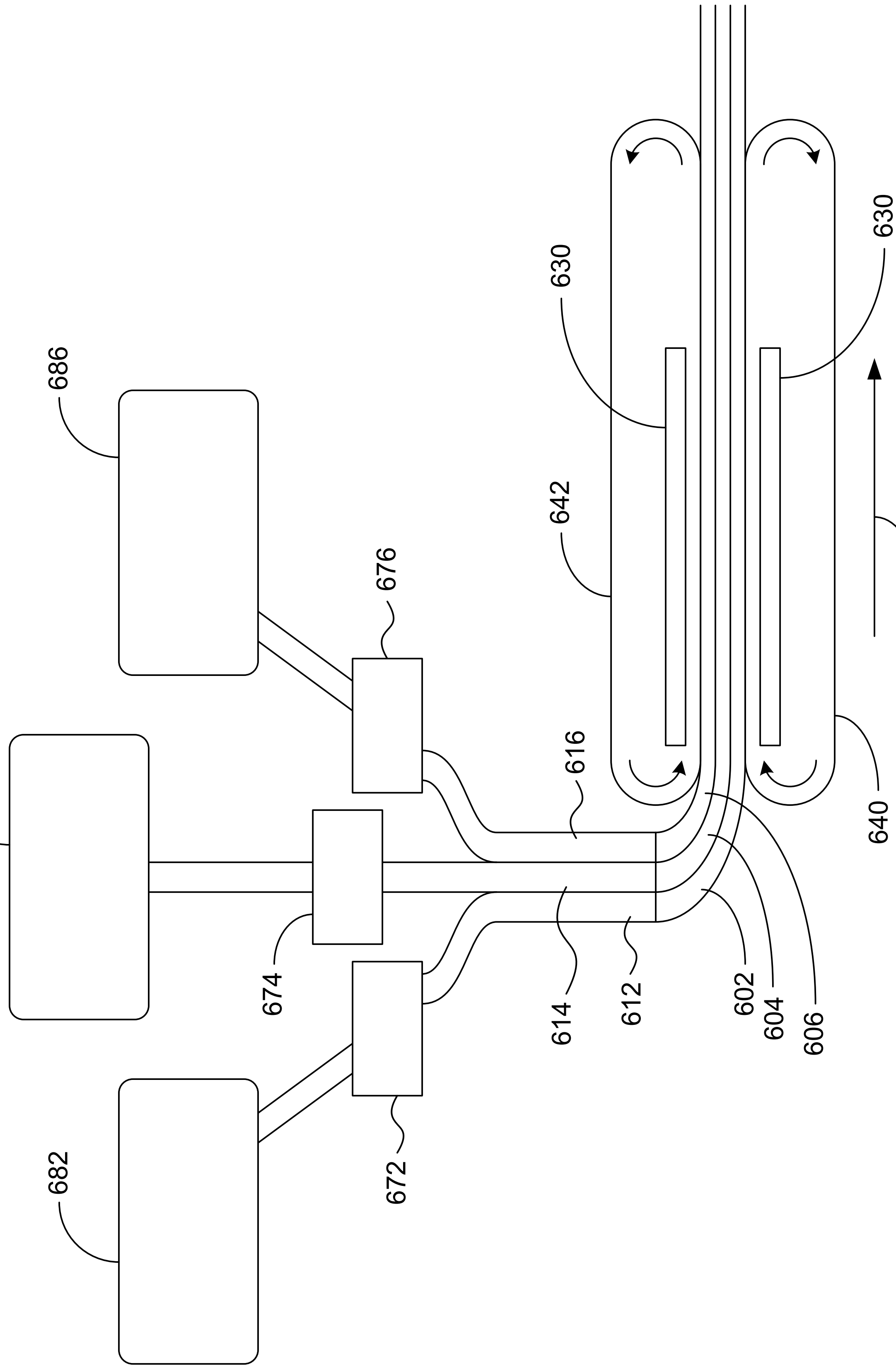
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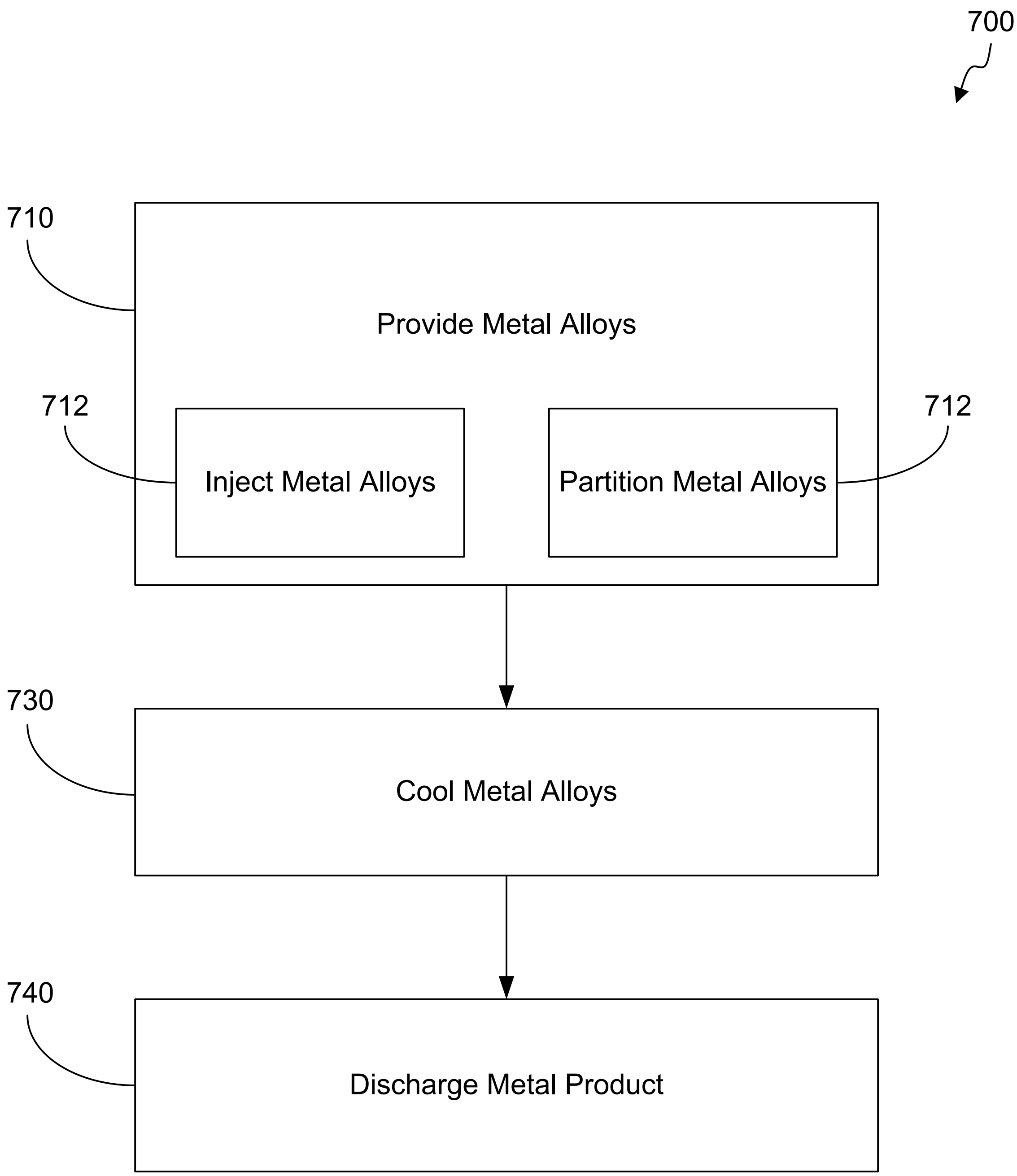
Figure 6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710
Provide Metal Alloys
712
Inject Metal Alloys
Partition Metal Alloys
712
730
Cool Metal Alloys
740
Discharge Metal Product

Figure 7