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Metal Products Exhibiting Improved Mechanical Properties and Methods of Making the Same

Samuel Robert Wagstaff

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METAL PRODUCTS EXHIBITING IMPROVED MECHANICAL PROPERTIES AND METHODS OF MAKING THE SAME

Technical Field

[0001] The present disclosure relates to metal stock and methods for producing metal stock, such as coils of metal strip, and more specifically to continuously cast recrystallized alloys containing dispersoids, as well as the processes for making such alloys.

Background

[0002] Dispersoids are collections of solid phases that are located within the primary phase of a solidified alloy. Dispersoids may help textural strengthening and other characteristics of aluminum alloys such as in a cast product like a metal strip. In a typical process to produce an alloy, dispersoid-forming elements such as Mn, Zr, Sc, Cr, V, or Hf precipitate and inhibit or retard recrystallization of the product during thermomechanical processing. Inhibiting recrystallization can increase the strength of the wrought product beyond that achieved by normal precipitation hardening. However, because recrystallization is inhibited due to dispersoid precipitation during homogenization of the as-cast material, the mechanical mixing that disrupts residual microsegregation is also inhibited. As a result, materials containing dispersoids ordinarily exhibit undesirable anisotropy and poor bend angle testing results, often fracturing when tested.

[0003] Direct chill (DC) casting and continuous casting (CC) are two exemplary methods of casting solid metal from liquid metal. In DC casting, liquid metal is poured into a mold having a retractable false bottom capable of withdrawing at the rate of solidification of the liquid metal in the mold, often resulting in a large and relatively thick ingot (e.g., 1500 mm x 500 mm x 5 m). The ingot can be processed, homogenized, hot rolled, cold rolled, annealed and/or heat treated, and otherwise finished before being coiled into a metal strip product distributable to a consumer of the metal strip product (e.g., an automotive manufacturing facility).

[0004] However, in DC casting, long homogenization cycles (e.g., 15 hours or more) are required to produce a desirable distribution of dispersoids. This long homogenization process is necessary in order to hot roll the alloy, because without it, the ingots are too brittle to economically roll. The homogenization process precipitates the dispersoid-forming elements, which then inhibit recrystallization of the material. However, as noted, because recrystallization in the product is inhibited, grains tend to become elongated and a distinct texture evolves. As a result, there can be

significant anisotropy in mechanical properties with respect to the rolling direction. While properties tested parallel to the rolling direction can be acceptable, properties diagonal and orthogonal to the rolling direction can be severely deteriorated.

[0005] Continuous casting involves continuously injecting molten metal into a casting cavity defined between a pair of moving opposed casting surfaces and withdrawing a cast metal form (e.g., a metal strip) from the exit of the casting cavity. In standard continuous casting products, dispersoids are often not present at all or present in small quantities which are unable to provide any beneficial effect. Additionally, even in cases where dispersoid forming elements are included in continuously cast materials, recrystallization in the continuously cast metal strips is inhibited due to the presence of the dispersoids, and the metal strips exhibit anisotropy in mechanical properties with respect to the rolling direction and poor VDA bend angle testing results as measured using VDA238-100, often fracturing almost immediately when tested.

Summary

[0006] Described herein are continuously cast recrystallized aluminum alloys containing dispersoids made using dispersoid-forming elements. These aluminum alloys exhibit isotropy with respect to mechanical properties, good bend angle testing results, and improved elongation. In some examples, the dispersoid-forming elements include one or more of Zr, Mn, Cr, V, Ti, Sc, Hf, Er, Yb, Tm, and/or Lu.

[0007] Also described herein are processes for producing recrystallized alloys by continuously casting a metal strip containing dispersoid-forming elements and adjusting and/or maintaining the temperature of the cast metal strip (e.g., by heating or cooling) to avoid exposing the metal strip to temperatures of about 350 °C or higher (e.g., from about 425 °C or higher or from about 350 °C to about 450 °C) for longer than about 1 hour to prevent formation of dispersoids at this stage. For example, the temperature of the cast metal strip can be adjusted and/or controlled to a temperature less than the recrystallization temperature of the cast metal strip (e.g., a temperature less than from about 0.3 to about 0.7 times the melting temperature of the metal strip). Then, the metal strip can be hot rolled at controlled times and temperatures to again prevent the formation of dispersoids (e.g., avoiding temperatures of about 350 °C to about 450 °C for more than about 1 hour) during the hot rolling step. In some aspects, after hot rolling, recrystallization can be performed, for example, by heating the rolled metal strip in a furnace or otherwise. In some

examples, recrystallization can be carried out at a temperature of from about 0.3 times the melting temperature of the metal to about 0.7 times the melting temperature of the metal (e.g., about 0.35 to about 0.65 times the melting temperature of the metal, about 0.4 to about 0.65 times the melting temperature of the metal, about 0.4 to about 0.6 times the melting temperature of the metal, or about 0.45 to about 0.6 times the melting temperature of the metal). Recrystallization can occur relatively rapidly after heating to a recrystallization temperature (e.g., after about 1 minute, about 2 minutes, about 3 minutes, about 4 minutes, about 5 minutes, about 6 minutes, about 7 minutes, about 8 minutes, about 9 minutes, about 10 minutes, about 11 minutes, about 12 minutes, about 13 minutes, about 14 minutes, or about 15 minutes, for example). The process should be controlled (for example through temperature and timing control) to ensure that the recrystallization occurs prior to any dispersoid precipitation. In some aspects, recrystallization can occur after hot rolling. In some aspects, recrystallization can occur during hot rolling.

[0008] After recrystallization, the metal strip can be heated (or continue to heat) to precipitate the dispersoid-forming elements and form dispersoids in the rolled metal strip. As described herein, formation of dispersoids does not occur until after recrystallization takes place. In some aspects, recrystallization can be considered to have occurred when greater than 50 % by volume of the metal strip has been recrystallized. In some examples, the dispersoids are precipitated at temperatures from about 330 °C to about 500 °C, (e.g., from about 350 °C to about 450 °C, from about 360 °C to about 440 °C, or from about 370 °C to about 430 °C). In some aspects, the precipitation of dispersoids can occur by heating at the appropriate temperature over a period of at least about 1 hour (e.g., at least 1.25 hours, at least 1.5 hours, at least 1.75 hours, at least 2 hours, at least 2.25 hours, at least 2.5 hours, at least 2.75 hours, at least 3 hours, or from 1 to 5 hours). The formation of dispersoids prevents further recrystallization of the metal strip, so that the initial recrystallization is preserved. Finally, the metal strip can be quenched to form a recrystallized continuously cast metal product containing dispersoids.

List of Figures

[0009] In the Figures, use of like reference numerals in different figures is intended to illustrate like or analogous components.

[0010] FIG. 1 is a schematic diagram depicting an exemplary metal casting and rolling system according to certain aspects of the present disclosure.

[0011] FIG. 2 is a chart showing bend angle results for alloys prepared according to the present disclosure and comparative alloys.

Detailed Description

[0012] Certain aspects and features of the present disclosure relate to continuously cast recrystallized alloys (e.g., aluminum alloys) that contain dispersoids and that exhibit isotropy with respect to mechanical properties and improved bend angle testing results. The dispersoids are formed in the alloys from dispersoid-forming elements. In some cases, the desired dispersoid-forming elements are transition metal elements, for example manganese (Mn), scandium (Sc), chromium (Cr), vanadium (V), hafnium (Hf), erbium (Er), iron (Fe), titanium (Ti), nickel (Ni), ytterbium (Yb), thulium (Tm), lutetium (Lu), and/or zirconium (Zr). Without being bound by theory, the dispersoids are formed from the precipitation of dispersoid-forming elements during heating, e.g., during post-recrystallization heating. Dispersoid-forming elements can be added to the aluminum alloy at levels above the saturation limit of the dispersoid-forming elements in the alloy in order to controllably form dispersoids during later heating (e.g., in the range of about 350 °C to about 450 °C for longer than about 1 hour).

[0013] The present disclosure also relates to the use and control of these dispersoid-forming elements in continuous casting and rolling processes, including steps of casting, rolling, recrystallizing, precipitating dispersoids and otherwise preparing metal products (e.g., a metal strip). By controlling factors such as the temperature of a metal product (e.g., an aluminum alloy) exiting a continuous caster and the time the metal product is maintained at higher temperature (e.g., a temperature greater than about 350 °C, greater than about 400 °C, a temperature greater than about 425 °C, or a temperature greater than the temperature of the metal strip exiting the continuous caster), the eutectic homogenization of the metal product can be completed or nearly completed, but peritectic homogenization (during which the dispersoid-forming elements precipitate) can be obstructed until after hot rolling and recrystallization. As used herein, nearly complete as related to the eutectic homogenization of the metal product upon exit of the continuous caster means that eutectic formers (e.g., Mg, Si, Zn, Cr) diffuse and precipitate. In this manner, dispersoid-forming elements can be maintained in solid solution during hot rolling at temperatures below about 425° C (e.g., from about 300 ° C to about 400 ° C, or from about 250 ° C to about 350°

C) so that recrystallization of the metal product can take place during or after hot rolling but before dispersoids precipitate.

[0014] Performing hot rolling at predetermined and controlled temperatures (while quenching the metal (e.g., aluminum alloy) during hot rolling as necessary to maintain the desired temperatures) provides insufficient conditions for the metal to dwell at an elevated temperature and for dispersoid-forming elements to precipitate within the metal matrix and form dispersoids. For example, dispersoid-forming elements present in the aluminum alloy can be frozen in a solutionized state by quenching after casting and/or quenching during hot rolling to maintain the alloy at a temperature below about 425° C (e.g., below about 400 ° C, below about 375 ° C, below about 350° C, for example. In some aspects, dispersoid formation in the aluminum alloy can be prevented by avoiding exposure of the aluminum alloy comprising dispersoid-forming elements to dispersoid-forming temperatures (e.g., above about 350 ° C, above about 375 ° C, above about 400 ° C, above about 425 ° C, or above about 450 ° C, for example) for periods of time longer than 30 minutes (e.g., longer than 1 hour, longer than 1.5 hours, longer than 2 hours, or longer than 3 hours). However, after recrystallization of the aluminum alloy has taken place, dispersoid formation can occur by exposure of the aluminum alloy comprising dispersoid-forming elements to these temperatures and times.

[0015] Recrystallization of the metal product during a post-hot rolling heat treatment step before allowing dispersoids to precipitate can result in desirable isotropic metal products (e.g., isotropic yield strength and/or isotropic VDA bending). The later precipitation of dispersoids (i.e., after recrystallization) with additional or continued heating prevents further recrystallization of the metal product beyond the initial recrystallization.

[0016] In some cases, desirable products can be achieved through continuous casting of an alloy containing at least one dispersoid-forming element; optional heating or cooling of the alloy using a quenching device to temperatures below the temperature at which dispersoids form (if maintained for sufficient time), for example, in some aspects, temperatures less than 425° C, e.g., less than 420° C, less than 410° C, less than 400° C, less than 390° C, less than 380° C, less than 375° C, less than 370° C, less than 360° C, less than 355° C, less than 350° C, less than 345° C, less than 340° C, less than 335° C, less than 330° C, less than 325° C, less than 320° C, less than 315° C, less than 310° C, less than 305° C, less than 300° C, less than 290° C, less than 275° C, or less than the recrystallization temperature of the alloy; inline hot rolling to reduce the thickness of

the metal strip approximately 40%-80%, for example (at temperatures less than about 425° C); recrystallization; and finally, dispersoid formation. In terms of ranges, the optional heating or cooling step before hot rolling can, in certain aspects, adjust the temperature of the alloy to temperatures from 270° C to 400° C, e.g., from 280° C to 380° C, between 290° C to 375° C, from 295° C to 370° C, from 300° C to 360° C, from 300° C to 355° C, from 300° C to 350° C, and from 310° C to 340° C. Preferably, the temperature of the alloy after casting and before hot rolling is from 300° C to 350° C.

[0017] Hot rolling at temperatures less than about 425° C (e.g., from about 250° C to about 400° C or from about 300° C to about 350° C) to maintain the dispersoid-forming elements in solution can be followed by a heat treatment step, e.g., heating to a recrystallization temperature, followed by further heating to effect homogenization and precipitation of the dispersoids. These desirable products can have beneficial shapes and sizes of intermetallic products that result in a product amenable to further processing, such as cold rolling, as well as customer use, such as bending and forming. The processes and resulting products are described further herein.

[0018] Aspects and features of the present disclosure are described herein with respect to producing metal strips, however aspects of the present disclosure may also be used to produce metal products of any suitable size or form, such as foils, sheets, slabs, plates, shates, or other metal products.

Definitions and Descriptions

[0019] In this description, reference is made to alloys identified by aluminum industry designations, such as “series” or “AA6xxx” or “6xxx.” For an understanding of the number designation system most commonly used in naming and identifying aluminum and its alloys, see “International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys” or “Registration Record of Aluminum Association Alloy Designations and Chemical Compositions Limits for Aluminum Alloys in the Form of Castings and Ingot,” both published by The Aluminum Association.

[0020] Reference is made in this application to alloy temper or condition. For an understanding of the alloy temper descriptions most commonly used, see “American National Standards (ANSI) H35 on Alloy and Temper Designation Systems.” An F condition or temper refers to an aluminum alloy as fabricated. A W condition or temper refers to an aluminum alloy

solution heat treated at a temperature greater than a solvus temperature of the aluminum alloy and then quenched. An O condition or temper refers to an aluminum alloy after annealing. An Hxx condition or temper, also referred to herein as an H temper, refers to a non-heat treatable aluminum alloy after cold rolling with or without thermal treatment (e.g., annealing). Suitable H tempers include HX1, HX2, HX3 HX4, HX5, HX6, HX7, HX8, or HX9 tempers. A T1 condition or temper refers to an aluminum alloy cooled from hot working and naturally aged (e.g., at room temperature). A T2 condition or temper refers to an aluminum alloy cooled from hot working, cold worked and naturally aged. A T3 condition or temper refers to an aluminum alloy solution heat treated, cold worked, and naturally aged. A T4 condition or temper refers to an aluminum alloy solution heat treated and naturally aged. A T5 condition or temper refers to an aluminum alloy cooled from hot working and artificially aged (at elevated temperatures). A T6 condition or temper refers to an aluminum alloy solution heat treated and artificially aged. A T7 condition or temper refers to an aluminum alloy solution heat treated and artificially overaged. A T8x condition or temper refers to an aluminum alloy solution heat treated, cold worked, and artificially aged. A T9 condition or temper refers to an aluminum alloy solution heat treated, artificially aged, and cold worked.

[0021] As used herein, the meaning of “room temperature” can include a temperature of from about 15 °C to about 30 °C, for example about 15 °C, about 16 °C, about 17 °C, about 18 °C, about 19 °C, about 20 °C, about 21 °C, about 22 °C, about 23 °C, about 24 °C, about 25 °C, about 26 °C, about 27 °C, about 28 °C, about 29 °C, or about 30 °C.

[0022] As used herein, terms such as “cast metal product,” “cast product,” “cast aluminum alloy product,” and the like are interchangeable and refer to a product produced by direct chill casting (including direct chill co-casting) or semi-continuous casting, continuous casting (including, for example, by use of a twin belt caster, a twin roll caster, a block caster, or any other continuous caster), electromagnetic casting, hot top casting, or any other casting method.

[0023] As used herein, a metal strip can be any type of metal product, for example, a plate, shate, or sheet.

[0024] As used herein, a plate generally has a thickness of greater than about 15 mm. For example, a plate may refer to an aluminum product having a thickness of greater than about 15 mm, greater than about 20 mm, greater than about 25 mm, greater than about 30 mm, greater than

about 35 mm, greater than about 40 mm, greater than about 45 mm, greater than about 50 mm, or greater than about 100 mm.

[0025] As used herein, a shate (also referred to as a sheet plate) generally has a thickness of from about 4 mm to about 15 mm. For example, a shate may have a thickness of about 4 mm, about 5 mm, about 6 mm, about 7 mm, about 8 mm, about 9 mm, about 10 mm, about 11 mm, about 12 mm, about 13 mm, about 14 mm, or about 15 mm.

[0026] As used herein, a sheet generally refers to an aluminum product having a thickness of less than about 4 mm. For example, a sheet may have a thickness of less than about 4 mm, less than about 3 mm, less than about 2 mm, less than about 1 mm, less than about 0.5 mm, or less than about 0.3 mm (e.g., about 0.2 mm).

[0027] As used herein, a recrystallized alloy can be any alloy that contains 50 % by volume or more of a recrystallized microstructure.

[0028] All ranges disclosed herein are to be understood to encompass any and all subranges subsumed therein. For example, a stated range of “1 to 10” should be considered to include any and all subranges between (and inclusive of) the minimum value of 1 and the maximum value of 10; that is, all subranges beginning with a minimum value of 1 or more, e.g. 1 to 6.1, and ending with a maximum value of 10 or less, e.g., 5.5 to 10.

Alloy Microstructure and Properties

[0029] Described herein are recrystallized alloys containing dispersoids made from continuous casting processes and having a novel microstructure. Aspects and features of the present disclosure can be used with any suitable metal, however may be especially useful when casting and rolling aluminum alloys. Specifically, desirable results can be achieved when casting alloys such as 2xxx series, 3xxx series, 4xxx series, 5xxx series, 6xxx series, 7xxx series, or 8xxx series aluminum alloys. For example, certain aspects and features of the present disclosure allow for more efficient and more reliable casting of 7xxx series alloys as compared to current casting methodologies.

[0030] In some aspects, the dispersoids are produced using at least one dispersoid-forming element. In some examples, the dispersoid-forming elements include one or more of Zr, Mn, Cr, V, Ti, Sc, Hf, Er, Yb, Tm, and/or Lu. In general, one or more of the transition elements (any of the set of metallic elements occupying a central block of Groups IVB-VIII, IB and IIB or 4-12 in the

periodic table) can serve as dispersoid-forming elements. In some cases, the alloy includes one or more of Mn, Zr, Sc, and Hf as the dispersoid-forming elements. In some examples, the dispersoids formed in the alloy comprise compounds of the formula Al_3M , where M is a dispersoid-forming element. In some non-limiting examples, the dispersoids include one or more of Al_3Zr , Al_3Mn , Al_3Cr , Al_3V , Al_3Ti , Al_3Sc , Al_3Hf , Al_3Er , Al_3Yb , Al_3Tm , or Al_3Lu . In other non-limiting examples, the dispersoids can have a composition according to one or more of the following formulae: AlX , $AlXX$, $AlXSi$, $Al(Fe,X)$, $Al(Fe,X)Si$, or the like, wherein each X is selected from the group consisting of Zr, Mn, Cr, V, Ti, Sc, Hf, Er, Yb, Tm, and/or Lu.

[0031] The dispersoids prevent recrystallization in the aluminum alloy. However, as noted, the processed alloys described herein are already in a recrystallized form when dispersoids are formed. Thus, according to the present disclosure, the dispersoids prevent further recrystallization so that the initial recrystallized structure is maintained.

[0032] A metal for continuous casting containing dispersoid-forming elements is an efficient precursor for a metal strip having desired dispersoid arrangements. The dispersoid distribution (formed by heating later in the process) can be controlled by adjusting the initial composition of dispersoid-forming elements in the metal for casting as well as the solidification rate of the metal during casting. For example, dispersoid-forming elements can be added to the metal for casting at levels above the saturation limit of dispersoid-forming elements in the metal in order to form dispersoids during later heating (e.g., in the range of about 350 °C to about 450 °C for longer than about 1 hour). According to the present disclosure, the later heating to form dispersoids occurs after casting and hot rolling the metal. Thus, after casting and hot rolling the metal, the cast and rolled metal strip containing dispersoid-forming elements can be heated to a sufficient temperature(s) (e.g., about 350° C, about 360° C, about 370° C, about 380° C, about 390° C, about 400° C, about 410° C, about 420° C, about 430° C, about 440° C, about 450° C, about 460° C, about 470° C, about 480° C, about 490° C, or about 500° C) to first preferentially recrystallize the metal strip and then to convert the recrystallized metal strip containing the matrix of dispersoid-forming elements into a metal strip containing dispersoids.

[0033] In some aspects, the dispersoids can have an even distribution of desired sizes (e.g., between approximately 10 nm and approximately 500 nm or between approximately 10 nm and approximately 100 nm). In other words, certain solidification and/or cooling aspects as disclosed herein can be used to prepare a cast metal strip or other cast metal product that can be hot rolled at

a temperature (e.g., below about 350° C, below about 375° C, below about 400° C, or below about 425° C) and/or a limited time (e.g., less than 2 hours, less than 1.5 hours, less than 1 hour, or less than 0.75 hours) to avoid the precipitation of dispersoid-forming elements, and then heated to preferentially recrystallize the metal strip and heated further to precipitate dispersoid-forming elements and form the desired dispersoid arrangement. Dispersoid distribution can be controlled through the initial composition of dispersoid-forming elements, as well as the solidification rate. For example, the solidification rate can be in the range of from about 50 °C/s to about 1200 °C/s, e.g., from about 80 °C/s to about 1100 °C/s, from about 100 °C/s to about 1000 °C/s, from about 100 °C/s to about 800 °C/s, from about 100 °C/s to about 600 °C/s, from about 100 °C/s to about 500 °C/s, or from about 200 °C/s to about 500 °C/s.

[0034] In some examples, after heating to precipitate the dispersoids, the dispersoids can be present in the aluminum alloy in a number density of at least about 10 dispersoids per square micrometer (μm^2) (e.g., at least about 13 dispersoids/ μm^2 , at least about 15 dispersoids/ μm^2 , at least about 13 dispersoids/ μm^2 , at least about 13 dispersoids/ μm^2 , at least about 17 dispersoids/ μm^2 , at least about 20 dispersoids/ μm^2 , at least about 25 dispersoids/ μm^2 , at least about 30 dispersoids/ μm^2 , at least about 35 dispersoids/ μm^2 , at least about 40 dispersoids/ μm^2 , at least about 45 dispersoids/ μm^2 , from about 10 dispersoids/ μm^2 to about 50 dispersoids/ μm^2 , from about 13 dispersoids/ μm^2 to about 40 dispersoids/ μm^2 , from about 13 dispersoids/ μm^2 to about 35 dispersoids/ μm^2 , or from about 15 dispersoids/ μm^2 to about 30 dispersoids/ μm^2). The number density will depend, in part, on the composition of the aluminum alloy. The number density can also depend on the rate of heating to precipitate the dispersoids. For example, a faster heat up rate can lead to a lower number density of dispersoids (but with a higher dispersoid diameter). In one example, a heating rate (to precipitate dispersoids) of about 20 °C/hr to a temperature of 470 °C can lead to an average dispersoid diameter of from about 20 nm to about 25 nm and a number density of dispersoids of about 20 dispersoids/ μm^2 to about 25 dispersoids/ μm^2 . In another example, a heating rate (to precipitate dispersoids) of about 50 °C/hr to a temperature of 470 °C can lead to an average dispersoid diameter of from about 33 nm to about 38 nm and a number density of dispersoids of about 10 dispersoids/ μm^2 to about 15 dispersoids/ μm^2 .

[0035] In some aspects, the dispersoids can have an average diameter of from about 5 nm to about 50 nm (e.g., from about 10 nm to about 50 nm, from about 10 nm to about 40 nm, from

about 15 nm to about 40 nm, from about 20 nm to about 35 nm, or from about 13 nm to about 35 nm).

[0036] In certain aspects, the grains of the recrystallized aluminum alloys containing dispersoids have a polygonal-shaped or spheroid grain structure.

[0037] The recrystallized and dispersoid-containing microstructures of the alloys described herein exhibit isotropy with respect to mechanical properties. That is, the alloys described herein have good mechanical properties in all directions (i.e., parallel, diagonal, and orthogonal to the rolling direction), not just parallel to the rolling direction as with other known alloys. The recrystallized and dispersoid-containing microstructures of the alloys described herein also lead to superior VDA bend angle testing results and improved elongation.

Methods of Preparing the Aluminum Alloys

[0038] The processes described herein can be suitable for providing a distributable coil of metal strip. A metal strip containing dispersoid-forming elements can be continuously cast from a continuous casting device, such as a belt caster, block caster or other casting device, optionally undergo post-casting heating or cooling, then undergo hot rolling, all without forming dispersoids by maintaining temperatures and/or times below the conditions at which dispersoids form in the metal strip (e.g., avoiding temperatures above about 350° C for more than about 1 hour, for example). During or after hot rolling, recrystallization can be carried out, for example, by heating the metal strip to a temperature of from about 0.3 times the melting temperature of the metal to about 0.7 times the melting temperature of the metal for a few minutes (e.g., about 10 minutes). After hot rolling and recrystallization, dispersoid precipitation can occur, after heating at similar temperatures to recrystallization (e.g., 0.3 times the melting temperature of the metal to about 0.7 times the melting temperature of the metal, or from about 350° C to about 450° C), but for a longer period of time (e.g., longer than 30 minutes, longer than 1 hour, longer than 1.5 hours, longer than 2 hours, or longer than 3 hours).

Continuous Casting

[0039] The casting device can be any suitable continuous casting device. For example, a belt casting device can be used, such as the belt casting device described in U.S. Patent No. 6,755,236 entitled "BELT-COOLING AND GUIDING MEANS FOR CONTINUOUS BELT

CASTING OF METAL STRIP,” the disclosure of which is hereby incorporated by reference in its entirety. In some cases, desirable results can be achieved by using a belt casting device having belts made from a metal having a high thermal conductivity, such as copper. The belt casting device can include belts made from a metal having a thermal conductivity of at least 250, 300, 325, 350, 375, or 400 watts per meter per Kelvin at casting temperatures, although metals having other values of thermal conductivity may be used. The casting device can cast a metal strip at any suitable thickness, for example thicknesses of approximately 7 mm to 50 mm.

[0040] In some cases, the casting device can be configured to provide solidification rates of at least at or about 1° C/s, at least at or about 5° C/s, at least at or about 10° C/s, at least at or about 25° C/s, at least at or about 50° C/s, or at least at or about 100° C/s) and fast cooling (e.g., quickly cooling at rates of at least at or about 1° C/s, at least at or about 5° C/s, at least at or about 10° C/s, at least at or about 25° C/s, at least at or about 50° C/s, or at least at or about 100° C/s) of the metal strip, which can facilitate improved microstructure in the final metal strip. In some cases, the solidification rate can be at or above 10 times the solidification rate of traditional DC casting.

[0041] Traditionally, fast solidification has been avoided because the resulting metal strip has undesirable characteristics. However, it has been surprisingly discovered that due to the speed of solidification as well as the slow diffusion of dispersoid-forming elements, continuously cast metal strips exhibit a fairly homogeneous structure with many of the dispersoid-forming elements in solution. In contrast, a DC cast ingot may have significant amounts of coring, which require homogenization for long periods of time. This fast solidification of continuously cast metal strips homogenizes eutectic-forming elements, but precipitates dispersoid-forming elements, preventing recrystallization. It is believed that fast solidification along with the slow diffusion of dispersoid-forming elements in alloys exiting a continuous casting line can, along with other techniques discussed herein, help ensure dispersoids are not able to form prior to recrystallizing the metal strip.

[0042] After casting, the metal strip can be cooled to a temperature lower than the strip’s recrystallization temperature, such as below 425 °C, or from 300° C to 350° C or from 300° C to 400° C, for example. As noted, due to the speed of solidification, these continuously cast products can exhibit a nearly homogenous structure with respect to many of the elements in solution. In some aspects, cooling this metal strip, such as immediately quenching of the metal strip as it exits the casting device, or shortly thereafter, can facilitate locking the dispersoid-forming elements in

solid solution. After cooling, for example to a temperature suitable for performing hot rolling without precipitating the dispersoids, the metal strip can then undergo hot rolling, also at a temperature to prevent precipitating the dispersoids (e.g., from 300 to 400° C, from 300 to 380° C, or from 300 to 350° C for example), as described in more detail below.

[0043] In some cases, solidification and cooling or heating can be performed singularly by a casting device. The casting device can be of sufficient length and have sufficient heat or heat removal characteristics to produce a metal strip to increase or reduce the temperature of the cast metal strip to at or below 425° C, 400° C, 375° C, 350° C, 325° C, 300° C, 275° C, 250° C, 240° C, 230° C, 220° C, 210° C, or 200° C, although other values may be used. Generally, such a casting device would have to either occupy significant space or operate at slow casting speeds. In some cases, where a smaller and faster casting device is desired, the metal strip can be quenched immediately after exiting the casting device or soon thereafter. The quench can occur sufficiently fast or quickly (e.g., cooling at greater 10 ° C/s, cooling at greater 25 ° C/s, or greater 50 ° C/s) to lock the dispersoid-forming elements in solution in the metal strip. Once the metal strip is ready to be further processed, it should be heated or cooled, if necessary, to a temperature sufficient to perform the hot work or rolling, but not precipitate the dispersoid-forming elements, for example to a temperature of less than 425° C, e.g., less than 420° C, less than 410° C, less than 400° C, less than 390° C, less than 380° C, less than 375° C, less than 370° C, less than 365° C, less than 360° C, less than 355° C, less than 350° C, less than 345° C, less than 340° C, less than 335° C, less than 330° C, less than 325° C, less than 320° C, less than 315° C, less than 310° C, less than 305° C, less than 300° C, less than 290° C, or less than 275° C. Preferably the temperature is less than 350° C.

[0044] In some aspects, the cast metal strip can be cooled or heated to a rolling temperature before it is hot rolled through one or more roll stands. In other aspects, the cast metal strip can be immediately hot rolled through one or more roll stands. As used herein, immediately can mean that the hot rolling process begins less than 15 minutes after completion of the casting process, e.g., less than 14 minutes after completion of the casting process, less than 13 minutes after completion of the casting process, less than 12 minutes after completion of the casting process, less than 11 minutes after completion of the casting process, less than 10 minutes after completion of the casting process, less than 9 minutes after completion of the casting process, less than 8 minutes after completion of the casting process, less than 7 minutes after completion of the casting

process, less than 6 minutes after completion of the casting process, less than 5 minutes after completion of the casting process, less than 4 minutes after completion of the casting process, less than 3 minutes after completion of the casting process, less than 2 minutes after completion of the casting process, or less than 1 minute after completion of the casting process, and optionally without any intervening steps.

[0045] In some cases, the metal strip can be heated at various points after being initially cast in the continuous casting process (e.g., by the continuous caster), so long as the metal strip remains below a temperature where dispersoids precipitate in the metal strip and/or below the recrystallization temperature of the metal strip (e.g., below about 425° C). Care should be taken to avoid precipitating dispersoids before hot rolling or other hot work is completed by, for example, maintaining the temperature of the metal strip below its recrystallization temperature. As mentioned, this allows for later recrystallization of the cast metal during a heat treatment after hot rolling (or other hot work) and prior to precipitation of dispersoids. In some cases, the system can include a cooling or heating device between the casting device and the rolling stand(s) to adjust the temperature of the cast metal strip to an appropriate one for rolling the cast metal strip while maintaining the dispersoid-forming elements in solution, for example, in some aspects, a temperature of less than about 425° C (e.g., less than about 425° C, less than about 400° C, less than about 375° C, less than about 350° C, from about 300 to about 400° C, from about 250 to about 300° C, such that the metal strip can be sufficiently rolled, but not precipitate dispersoids, ultimately resulting in a metal strip with isotropic mechanical properties ((e.g., isotropic yield strength) and good bending and elongation behavior.

Hot Working (e.g., Hot Rolling)

[0046] After casting and optional cooling or heating, the metal strip containing dispersoid-forming elements can be fed into a hot rolling mill to be reduced to a desired thickness. With continuous casting, the as-cast metal strip can be fed directly into a hot rolling mill, unlike DC casting. By carefully controlling conditions such as the temperature of the continuously cast metal strip before and during further processing (e.g., hot rolling), the dispersoid-forming elements can be maintained in solution while significant hot work, such as hot rolling, is performed. As discussed in more detail below, upon later heating to homogenize the metal, the material can

recrystallize, followed by precipitation of dispersoids which then inhibit further recrystallization. Different from other processes, a hot rolling step is performed before dispersoid precipitations.

[0047] As explained above, the temperature of the metal strip before entering the hot rolling system can be below the point where dispersoid-forming elements precipitate, for example less than 425° C, e.g., less than 420° C, less than 410° C, less than 400° C, less than 390° C, less than 380° C, less than 375° C, less than 370° C, less than 360° C, less than 355° C, less than 350° C, less than 345° C, less than 340° C, less than 335° C, less than 330° C, less than 325° C, less than 320° C, less than 315° C, less than 310° C, less than 305° C, less than 300° C, less than 290° C, or less than 275° C. Yet the temperature should be high enough to allow for sufficient hot work (e.g., hot rolling) of the strip to be performed.

[0048] The hot rolling process can include one or more hot rolling stands, each including work rolls for applying force to reduce the thickness of the metal strip. In some cases, the total amount of reduction of thickness during hot rolling can be at or less than approximately 80%, 70%, 65%, 60%, 55%, 50%, 45%, 40%, 35%, 30%, 25%, 20% or 15%, although other values may be used. The hot rolling can be performed at a relatively high speed, such as an entry speed (e.g., speed of the metal strip as it enters the first hot roll stand) of about 1 to around 20 meters per minute (m/min), although other entry speeds can be used. The exit speed (e.g., speed of the metal strip as it exits the last hot roll stand) can be much faster due to the percentage of reduction of thickness imparted by the hot roll stand(s), such as about 5 to around 500 m/min, although other exit speeds may occur. For desirable results, hot rolling can be performed at a hot rolling temperature. The hot rolling temperature can be at or below about 400° C, such as from 300° C to 360° C, from 330° C to 370° C, from 330° C to 380° C, from 300° C to 400° C, or from 250° C to 400° C, although other ranges may be used so long as the temperature is controlled to prevent dispersoids from precipitating out of solution. In some cases, the hot rolling temperature can be controlled and maintained below the alloy recrystallization temperature and/or below the temperature at which dispersoids precipitate in the metal strip.

[0049] The hot band product can be at final gauge, at final gauge and temper, or can be ready for further processing, such as heat treatment and/or cold rolling. In some cases where the cast metal strip to be rolled is at a relatively low temperature, for example below 300° C, an inline furnace can be helpful to facilitate taking a higher reduction of thickness during the hot rolling. However, care should be taken not to precipitate dispersoids during heating or hot rolling and

before the metal product has been recrystallized, such as by using too high a rolling temperature for example (e.g., a temperature above the recrystallization temperature of the metal). As used herein, the term reduction of thickness can be a form of reduction of section that is performed using rolling. Other types of reduction of section can include reduction of diameter for extruded metal products. Hot rolling can be a type of hot working. Other types of hot working can include hot extruding.

Post-rolling Processing

[0050] After hot working, the rolled metal strip can be reheated, for example with a heat treatment step, and quenched prior to coiling for delivery. For example, the rolled metal strip can be homogenized by heating in a heat treatment step. The heating for homogenizing can first cause recrystallization of the rolled metal strip. As the homogenization continues, the dispersoid-forming elements in the recrystallized rolled metal strip precipitate, inhibiting further recrystallization. In some examples, the heating step after hot rolling first recrystallizes the metal strip and then quickly induces the precipitation of evenly distributed and desirably-sized dispersoids. This final coiled metal strip can be of the desired gauge and have the desired physical characteristics for distribution. In some cases, the metal strip is cold rolled after the heat treatment step to obtain the desired gauge before coiling.

[0051] Thus, after passing through the hot rolling stands, the metal strip can be heated to a post-rolling or heat treatment temperature. The post-rolling temperature can differ depending on the alloy, but may be about 350 ° C, about 360° C, about 370° C, about 380° C, about 390° C, about 400° C, about 410° C, about 420° C, about 430° C, about 440° C, about 450° C, about 455° C, about 460° C, about 470° C, about 480° C, about 490° C, about 500° C, about 510° C, about 520° C, or about 530° C. In any case, the temperature should be sufficient to first recrystallize the metal strip and then precipitate dispersoid-forming elements. The time for recrystallization can be on the order of a few minutes (e.g., about 1 minute, about 2 minutes, about 3 minutes, about 4 minutes, about 5 minutes, about 6 minutes, about 7 minutes, about 8 minutes, about 9 minutes, about 10 minutes, about 12 minutes, about 14 minutes, about 15 minutes, about 18 minutes, about 20 minutes, about 22 minutes, about 24 minutes, about 25 minutes, about 28 minutes, or about 30 minutes). Dispersoid precipitation can occur after heating at similar temperatures to recrystallization (e.g., 0.3 times the melting temperature of the metal to about 0.7 times the melting

temperature of the metal, or from about 350° C to about 500° C), but after a longer period of time at the temperature (e.g., longer than 30 minutes, longer than 1 hour, longer than 1.5 hours, longer than 2 hours, or longer than 3 hours).

[0052] In some cases, recrystallization occurs even before a heat treatment step. For example, dynamic recrystallization during hot rolling can occur by applying sufficient force to induce sufficient strain on the metal product during rolling at a particular temperature to recrystallize the metal product. Dynamic recrystallization can enable the metal strip to be quenched immediately after hot rolling, without needing to reheat the metal strip (e.g., to above a recrystallization temperature) to achieve recrystallization and precipitate the dispersoids. Instead of relying on post-rolling (e.g., after hot rolling) recrystallization during a heat treatment process, which can require a temperature increase prior to quenching, a metal strip can undergo dynamic recrystallization during the hot rolling process, as described herein. However, dispersoids should be maintained in solution during the hot rolling process until recrystallization is completed, by, for example, maintaining the temperature of the metal strip during the rolling and dynamic recrystallization below a temperature at which dispersoids precipitate, for example less than 425° C, less than 400° C, less than 375° C, less than 350° C, less than 325° C, less than 300° C, less than 275° C, less than 250° C, less than 240° C, less than 230° C, less than 220° C, less than 210° C, or less than 200° C. In the case of dynamic recrystallization, according to the present disclosure, dispersoids can precipitate with heating (or maintaining sufficient temperature for extended times) after recrystallization but before quenching.

[0053] Dynamic recrystallization can involve rolling the metal strip at a sufficiently high strain rate and at sufficiently high temperature. Dynamic recrystallization can occur in the final rolling stand of the hot rolling mill. Dynamic recrystallization is dependent upon the strain rate and temperature of the metal strip being processed. The Zener-Hollomon parameter (Z) can be defined by the equation $Z = \dot{\epsilon} \exp \frac{Q}{RT}$, where $\dot{\epsilon}$ is the strain rate, Q is the activation energy, R is the gas constant, and T is the temperature. Recrystallization occurs when the Zener-Hollomon parameter falls within a desired range. To remain within this range while minimizing temperature (e.g., hot rolling exit temperature), a metal strip must undergo higher strain rates than would be necessary at higher temperatures. Therefore, it can be desirable to maximize the amount of reduction (e.g., percentage thickness reduction) of the final hot rolling stand or at least select an amount of reduction suitable to achieve a hot rolling exit temperature suitable for rapid quenching

to minimize time spent within the zone of high precipitation. To achieve the desired total reduction of thickness, the amount of reduction of thickness added to the final hot rolling stand can be offset by decreasing the amount of reduction of thickness provided by one or more of the preceding hot rolling stands.

[0054] When using a post-rolling heat treatment, immediately after reheating the metal strip at the post-rolling heat treatment temperatures to precipitate the dispersoids, or shortly thereafter, the metal strip can be quenched. The metal strip can be quenched down to a coiling temperature, which can be at or below 150° C, 140° C, 130° C, 120° C, 110° C, or 100° C, although other values may be used. In some embodiments, the metal strip can also be cold rolled to a final gauge. The metal strip may then be coiled for delivery. At this point, the coiled metal strip may have the desired physical characteristics for distribution, such as a desired gauge and a desired temper.

[0055] The result of the casting, hot rolling, recrystallizing, and precipitating dispersoid process is a metal strip that can have the characteristics desired for a particular customer. In some embodiments, the metal strip can also be cold rolled to a desired final gauge. The metal strip can be coiled and distributed, such as to an automotive plant capable of forming automotive parts from the metal strip. Certain aspects of the present disclosure relate to a metal strip and systems and methods for forming a recrystallized metal strip having desirable dispersoids (e.g., a desirable distribution of dispersoids of a desirable size).

[0056] In some aspects of the present disclosure, manipulation of one or more of the solidification rate, cooling (e.g., quenching) rate, and heating time can be used to specifically tailor dispersoid size and distribution on demand. A controller can be coupled to systems to control solidification rate, cooling rate, rolling temperatures, and reheating time. When a metal strip is desired to have a certain characteristic attributable to a particular dispersoid arrangement (e.g., size and/or distribution), the controller can manipulate the various rates/times to produce the desired metal strip. In this fashion, metal strips with desired dispersoid arrangements can be created on demand. Because control of dispersoid arrangements can provide for more or less efficiency in how alloying elements are leveraged, on demand control of dispersoid arrangements can enable a controller to compensate for deviations in alloying elements of a particular mixture of liquid metal. For example, when producing deliverable metal strips having certain desired characteristics, a controller may compensate for slight deviations in the concentrations of alloying elements between

casts by adjusting the solidification rate, cooling rate, rolling temperatures and/or reheating time of the system to produce dispersoid arrangements that provide for more or less efficient usage of the alloying elements (e.g., more efficient usage may be desirable when a negative deviation of alloying elements is determined). Such compensation can be performed automatically or can be automatically recommended to a user.

Casting, Hot Rolling, and Heat Treatment Systems

[0100] In one example, a casting system can include a continuous caster, an optional quenching or heating device, one or more hot roll stands, a post-rolling heat treatment device, and a coiler. In some cases, one or more quenches can occur before and/or after the hot roll stand. A quench before the hot rolling stand may be optional in order to lower the temperature of the metal strip to a temperature that will not precipitate dispersoids before or during hot rolling such as less than 425° C, less than 400° C, less than 375° C, less than 350° C, less than 325° C, less than 300° C, less than 275° C, less than 250° C, less than 240° C, less than 230° C, less than 220° C, less than 210° C, or less than 200° C, for example.

[0101] In some cases, the rolling stand(s) of the hot rolling system are cooled, such as through a coolant system including nozzles that spray coolant onto the rolls of the rolling stand(s) and/or the metal strip itself. In some aspects, this coolant system may extract sufficient heat such that the mechanical action of reducing the thickness of the metal strip by passing the metal strip through the hot rolling stand(s) does not increase the temperature of the metal strip to a temperature at which dispersoids will precipitate.

[0102] FIG. 1 is a schematic diagram depicting an exemplary metal casting and rolling process 5 according to certain aspects of the present disclosure. The metal casting and rolling process 5 includes continuously casting 20 a material 10, such as an aluminum alloy containing dispersoid-forming elements, into a metal strip. Continuous casting 20 can include continuous casting using a continuous casting device, such as a continuous belt caster that continuously casts a metal strip or other suitable continuous caster. After being continuously cast, the metal strip undergoes a hot rolling step 30. Before being hot rolled, the metal strip can be cooled or heated 25 to a temperature sufficient to perform hot rolling, but not precipitate dispersoids (e.g., to a temperature less than 425° C, to a temperature less than 400° C, to a temperature less than 375° C, from 300 to 350° C). That is, before being hot rolled at step 30, the temperature and the time at

temperature of the metal strip should be controlled so that conditions at which dispersoids will precipitate are avoided, for example less than 425° C, less than 400° C, less than 375° C, less than 350° C, less than 325° C, less than 300° C, less than 275° C, less than 250° C, less than 240° C, less than 230° C, less than 220° C, less than 210° C, or less than 200° C, for less than 2 hours, less than 1.5 hours, less than 1.25 hours, less than 1 hour, or less than 0.75 hours, for example. Cooling the temperature of the metal strip can be performed by a quenching system 25, for example.

[0103] Hot rolling at step 30 can reduce the thickness of the metal strip from an as-cast gauge to a desired gauge for distribution. In some cases, the desired gauge for distribution can be at or approximately 0.7 mm to 4.5 mm, or at or approximately 1.5 mm to 3.5 mm. Hot rolling 30 can be done using one or more hot rolling stands, for example, for reducing the thickness of the metal strip. As described above, the temperature of the hot rolling 30 can be controlled so it remains below a temperature at which dispersoids will precipitate (e.g., less than about 425° C, less than about 400° C, less than about 375° C, less than about 350° C, less than about 325° C, less than about 300° C, less than about 275° C, less than about 250° C, less than about 240° C, less than about 230° C, less than about 220° C, less than about 210° C, or less than about 200° C).

[0104] After hot rolling 30, the metal alloy undergoes post-hot rolling heat treatment 60. The heat treatment 60 applies initial heating 35 to perform a recrystallization 40 of the metal strip (e.g., at a temperature of from about 0.3 times the melting temperature of the metal to about 0.7 times the melting temperature of the metal for about 10 minutes). Following the recrystallization 40 of the metal strip, further heat treating 45 (at the same or similar temperatures to the recrystallization) for longer time periods (e.g., at least about 0.5 hours, at least about 0.75 hours, at least about 1 hour, at least about 1.25 hours, at least about 1.5 hours, at least about 1.75 hours, or at least about 2 hours) can be applied to precipitate dispersoids 50 (e.g., at temperatures at or around 425° C or above). The metal strip exiting the post-hot rolling or heat treatment system can be provided directly to further processing equipment (e.g., a blanking machine or a bending machine) and can ultimately be turned into a distributable coil (e.g., a finished coil). In some cases, the metal strip can be subjected to further rolling, such as cold rolling, or other processing before coiling.

Examples

[0105] Aluminum alloys were prepared with the compositions as listed in Table 1, with impurities totaling up to 0.15 wt. % and the remainder Al. All values are provided in wt. %. Examples 1-4 (“Ex. 1-4”) were prepared according to the present disclosure. Examples 1-4 were produced by a continuous casting process and immediately hot rolled in a hot rolling mill and then cooled and coiled. Examples 1-4 were then reheated at 480 °C for 2 hours to recrystallize and precipitate dispersoids before hot rolling to a final gauge of 2.0 mm (e.g., hot rolling to gauge so that the rolling starts hot and finishes cold). Comparative Examples 1-4 (“Comp. 1-4”) were prepared according to a standard method in the art. Comparative Examples 1-4 were produced by a continuous casting process and immediately hot rolled in a hot rolling mill and then cooled and coiled. Finally, Comparative Examples 1-4 were 67% cold rolled to a final gauge of 2.0 mm.

Table 1

	Cu	Fe	Mg	Mn	Si	Ti	Cr	V	Zn	Zr
Ex. 1 and Comp. 1	0.59	0.18	3.49	0.09	0.05	0.01	0.09	0.01	4.50	0.12
Ex. 2 and Comp. 2	1.56	0.18	2.58	0.04	0.05	0.01	0.09	0.01	6.80	0.12
Ex. 3 and Comp. 3	1.70	0.20	2.60	0.07	0.10	0.02	0.04	0.00	5.90	0.12
Ex. 4 and Comp. 4	1.20	0.20	2.30	0.05	0.10	0.01	0.03	0.00	9.20	0.10

VDA Bending Testing

[0106] Testing was performed using bending tests were conducted on the Examples 1-4 and Comparative Examples 1-4 according to the 238-100 specification of the German Association of the Automotive Industry (VDA) for performing bending tests and the 232-200 specification for normalizing the tests to 2.0 mm. Results are shown in FIG. 2. Comparative Examples 2-4 were observed to break before achieving any bend. It was also observed that bending behavior was significantly improved for Examples 2-4 over Comparative Examples 2-4. Bending behavior for Example 1 was similar to Comparative Example 1.

FIG. 1

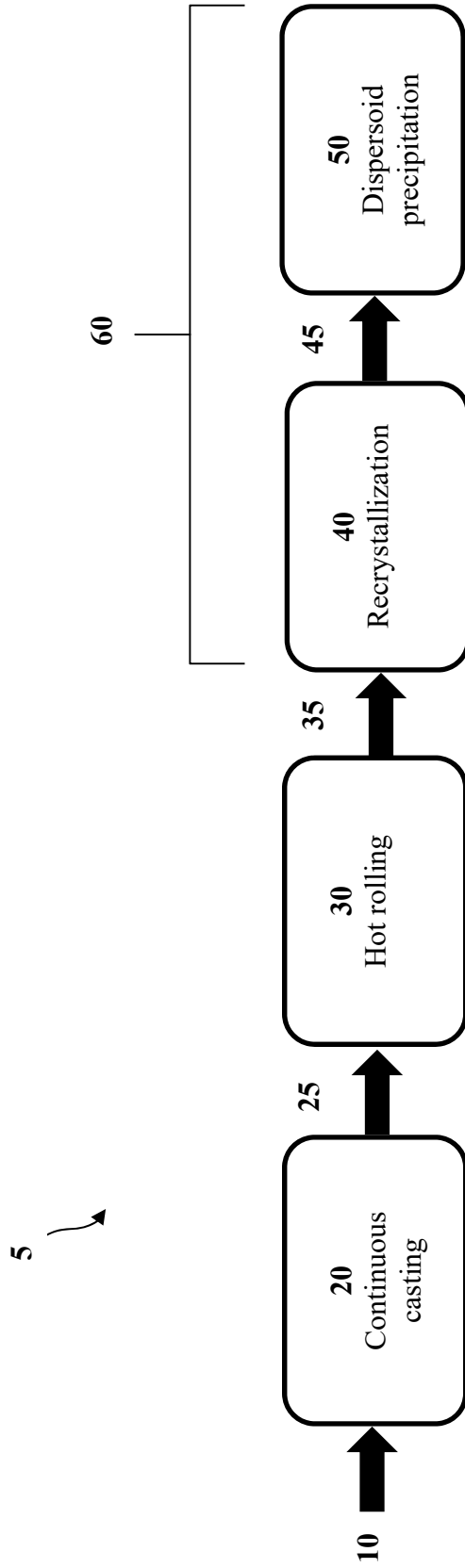


FIG. 2

