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(54) **Titre : ARTICLE EN ALLIAGE D'ALUMINIUM A FAIBLE FORMATION DE STRIES ET PROCEDES DE FABRICATION ASSOCIES**
(54) **Title: ALUMINUM ALLOY ARTICLE HAVING LOW ROPING AND METHODS OF MAKING THE SAME**

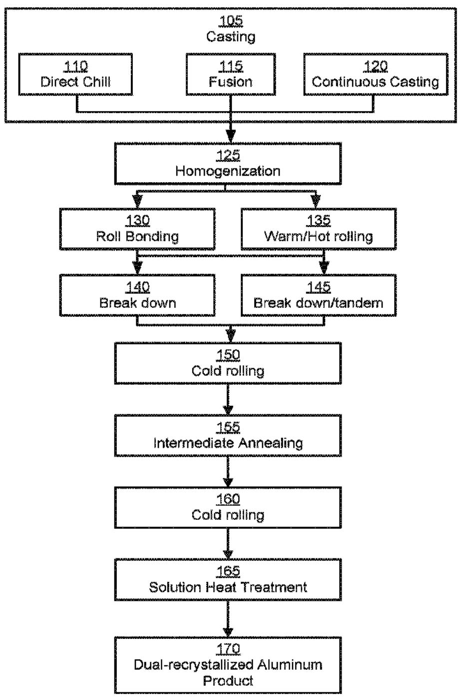

FIG. 1

(57) **Abrégé/Abstract:**
Provided herein are aluminum alloys having low roping. Also provided herein are methods to produce aluminum alloys having low roping, which may include subjecting an unrecrystallized aluminum product to an annealing heat treatment at a predefined temperature of less than or equal to 495 °C for a length of time less than or equal to 25 minutes to generate a recrystallized aluminum product.

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(54) **Title:** ALUMINUM ALLOY ARTICLE HAVING LOW ROPING AND METHODS OF MAKING THE SAME

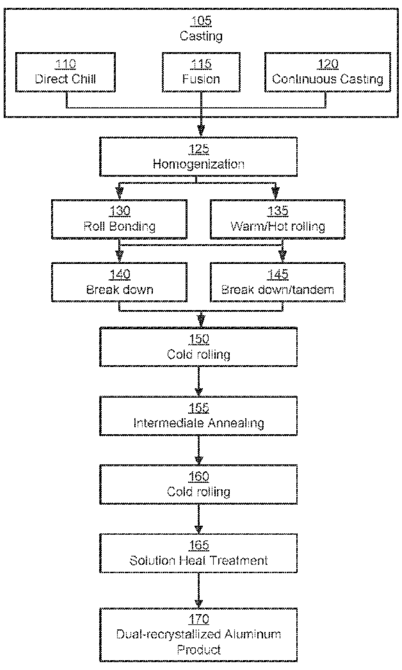

FIG. 1

(57) **Abstract:** Provided herein are aluminum alloys having low roping. Also provided herein are methods to produce aluminum alloys having low roping, which may include subjecting an unrecrystallized aluminum product to an annealing heat treatment at a predefined temperature of less than or equal to 495 °C for a length of time less than or equal to 25 minutes to generate a recrystallized aluminum product.

WO 2023/039141 A1

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WO 2023/039141 A1

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

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ALUMINUM ALLOY ARTICLE HAVING LOW ROPING AND METHODS OF MAKING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to U.S. Provisional Application No. 63/261,042, filed on September 9, 2021, which is hereby incorporated by reference in its entirety.

FIELD

[0002] The present disclosure relates to metallurgy generally and more specifically to aluminum alloys and aluminum alloy products having low roping. In addition, the disclosure also provides methods of making aluminum alloy products, including those having low roping.

BACKGROUND

[0003] Aluminum alloy articles are desirable for use in a number of different applications, such as those where strength and durability are especially desirable. For example, aluminum alloys are commonly used for automotive skin panels and structural applications in place of steel. Because aluminum alloys are generally about 2.8 times less dense than steel, the use of such materials reduces the weight of the vehicle and allows for substantial improvements in its fuel economy. Even so, the use of currently available aluminum alloys in automotive and other applications poses certain challenges.

[0004] One such challenge for skin applications relates to forming automotive components with high elongation and improved surface quality (e.g., low roping) for high bendability for assembly of the automotive components. Surface quality and bendability improvement may be achieved with continuous inter-annealing at high temperatures (e.g., above 540 °C), or with batch inter-annealing at lower temperatures for a longer length of time (e.g., two hours).

[0005] Roping is a strain-induced roughness or a macroscopic surface roughening defect. Roping can be characterized by visible lines that may be several centimeters wide along the rolling direction. Roping can result from materials being stretched along a transverse direction. The surface distribution of ridges and valleys can limit the use of the materials for outer panels in vehicle applications.

SUMMARY

[0006] The term embodiment and like terms are intended to refer broadly to all of the subject matter of this disclosure and the claims below. Statements containing these terms should be understood not to limit the subject matter described herein or to limit the meaning or scope of the claims below. Embodiments of the present disclosure covered herein are defined by the claims below, not this summary. This summary is a high-level overview of various aspects of the disclosure and introduces some of the concepts that are further described in the Detailed Description section below. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this disclosure, any or all drawings and each claim.

[0007] In a first aspect, methods for producing dual-recrystallized aluminum products are disclosed. The dual-recrystallized aluminum products may have bending and elongation properties allowing for good performance when used. The dual-recrystallized aluminum products may also or alternatively exhibit a roping-free or low roping character.

[0008] Example methods may comprise providing an unrecrystallized aluminum product and subjecting the unrecrystallized aluminum product to an intermediate annealing heat treatment. The intermediate annealing heat treatment can be performed at a predefined temperature of less than or equal to 400 °C for a length of time less than or equal to 25 minutes to generate a first recrystallized aluminum product.

[0009] In some cases, the first recrystallized aluminum product may be processed to achieve desired properties after the first recrystallization. For example, the first recrystallized aluminum product may be processed, such as cold rolled, to generate a rolled product. The processing may achieve a cold reduction from 40% to 99%. Additional processing may include performing a solution heat treatment on the first recrystallized aluminum product to generate a dual-recrystallized aluminum product.

[0010] The dual-recrystallized aluminum product may exhibit particular properties to achieve the desired performance. For example, the dual-recrystallized aluminum product can optionally exhibit an f10% bending value of at most 0.55 in a transverse direction or an f15% bending value of at most 0.70 in a transverse direction. The dual-recrystallized aluminum

product may additionally or alternatively exhibit a surface arithmetical mean height (Sa) of at most 0.50 μm or a uniform elongation of at least 21%. Other examples of properties of the dual-recrystallized aluminum product optionally include an average undissolved precipitate size of from 0.05 μm to 0.5 μm, undissolved precipitates occupying an area fraction of from 0% to 1%, microvoids occupying an area fraction of from 0% to 0.3%, and/or a conductivity of from 25 mΩ/m to 40 mΩ/m.

[0011] In some cases, the particular properties are achieved by or at least partly as a consequence of the intermediate annealing heat treatment. Optionally, the predefined temperature of the intermediate annealing heat treatment may be at most 350 °C and the length of time of the intermediate annealing heat treatment may be at most ten minutes or at most five minutes. The intermediate annealing heat treatment may comprise passing the unrecrystallized product through a furnace, such as a gas-fired furnace, at a speed of from 5 m/min to 200 m/min. In other cases, the intermediate annealing heat treatment can comprise heating the unrecrystallized aluminum product using a magnetic heating or an electric induction process.

[0012] Optionally, the unrecrystallized aluminum product comprises a 6xxx series aluminum alloy or a 1xxx, 2xxx, 3xxx, 4xxx, 5xxx, 7xxx, or 8xxx series aluminum alloy. In some aspects, a thickness of the unrecrystallized aluminum product is from 0.1 mm to 5.0 mm, such as prior to the intermediate annealing heat treatment. The unrecrystallized aluminum product may comprise a hot-rolled aluminum product and/or a cold-rolled or partially cold-rolled aluminum product. The cold-rolled aluminum product can correspond to a cold reduction of from 5% to 99%.

[0013] Other objects and advantages will be apparent from the following detailed description of non-limiting examples.

BRIEF DESCRIPTION OF THE FIGURES

[0014] The specification makes reference to the following appended figures, in which use of like reference numerals in different figures is intended to illustrate like or analogous components.

[0015] FIG. 1 provides a schematic overview of an example method for making a dual-recrystallized aluminum alloy product.

[0016] FIG. 2 provides a schematic overview of a process for preparing aluminum alloy articles.

[0017] FIG. 3 provides an overview of an example method for producing a recrystallized aluminum product.

[0018] FIG. 4A and FIG. 4B provide schematic illustrations of an unrecrystallized aluminum alloy product and a recrystallized aluminum alloy product.

[0019] FIG. 5A, FIG. 5B, FIG. 5C, FIG. 5D, FIG. 5E, and FIG. 5F provides graphs comparing strength properties of aluminum alloys produced according to certain aspects of the present disclosure.

[0020] FIG. 6A, FIG. 6B, FIG. 6C, FIG. 6D, FIG. 6E, FIG. 6F, FIG. 6G, and FIG. 6H provide graphs comparing elongation properties of aluminum alloys produced according to certain aspects of the present disclosure.

[0021] FIG. 7A, FIG. 7B, FIG. 7C, FIG. 7D, FIG. 7E, FIG. 7F, FIG. 7G, provide graphs comparing bending, Lankford ratio, and surface characteristics of aluminum alloys produced according to certain aspects of the present disclosure.

[0022] FIG. 8 provides graphs of surface characteristics of aluminum alloys produced according to certain aspects of the present disclosure.

[0023] FIG. 9A, FIG. 9B, and FIG. 9C provide images of aluminum alloys produced according to certain aspects of the present disclosure.

[0024] FIG. 10A and FIG 10B provide additional images of aluminum alloys produced according to certain aspects of the present disclosure.

[0025] FIG. 11A and FIG. 11B provides graphs comparing precipitate properties and conductivity of aluminum alloys produced according to certain aspects of the present disclosure.

[0026] FIG. 12 provides micrograph images of aluminum alloys produced according to certain aspects of the present disclosure.

[0027] FIG. 13A and FIG. 13B provide graphs comparing statistics from the microstructure of aluminum alloys produced according to certain aspects of the present disclosure.

[0028] FIG. 14 provides another graph comparing statistics from the microstructure of aluminum alloys produced according to certain aspects of the present disclosure.

DETAILED DESCRIPTION

[0029] Described herein are methods and aluminum alloy articles that exhibit a novel combination of bending properties, elongation properties, microstructure, and methods of making such articles. These articles can be produced using a fast, low temperature inter-annealing heat treatment. Resulting roping, bending, and elongation properties can, in some cases, be similar to those produced from fast, high temperature annealing or slow, low temperature annealing processes.

Definitions and Descriptions:

[0030] As used herein, the terms “invention,” “the invention,” “this invention” and “the present invention” are intended to refer broadly to all of the subject matter of this patent application and the claims below. Statements containing these terms should be understood not to limit the subject matter described herein or to limit the meaning or scope of the patent claims below.

[0031] In this description, reference is made to alloys identified by AA numbers and other related designations, such as “series” or “7xxx.” 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.

[0032] 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.

[0033] 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.

[0034] 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).

[0035] Reference may be 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. 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. A W condition or temper refers to an aluminum alloy after solution heat treatment.

[0036] 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.

[0037] 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. As used herein, the meaning of “ambient conditions” can include temperatures of about room temperature, relative humidity of from about 20% to about 100%, and barometric pressure of from about 975 millibar (mbar) to about 1050 mbar. For example, relative humidity can be about 20%, about 21%, about 22%, about 23%, about 24%, about 25%, about 26%, about 27%, about 28%, about 29%, about 30%, about 31%, about 32%, about 33%, about 34%, about 35%, about 36%, about 37%, about 38%, about 39%, about 40%, about 41%, about 42%, about 43%, about 44%, about 45%, about 46%, about 47%, about 48%, about 49%, about 50%, about 51%, about 52%, about 53%, about 54%, about 55%, about 56%, about 57%, about

58%, about 59%, about 60%, about 61%, about 62%, about 63%, about 64%, about 65%, about 66%, about 67%, about 68%, about 69%, about 70%, about 71%, about 72%, about 73%, about 74%, about 75%, about 76%, about 77%, about 78%, about 79%, about 80%, about 81%, about 82%, about 83%, about 84%, about 85%, about 86%, about 87%, about 88%, about 89%, about 90%, about 91%, about 92%, about 93%, about 94%, about 95%, about 96%, about 97%, about 98%, about 99%, about 100%, or anywhere in between. For example, barometric pressure can be about 975 mbar, about 980 mbar, about 985 mbar, about 990 mbar, about 995 mbar, about 1000 mbar, about 1005 mbar, about 1010 mbar, about 1015 mbar, about 1020 mbar, about 1025 mbar, about 1030 mbar, about 1035 mbar, about 1040 mbar, about 1045 mbar, about 1050 mbar, or anywhere in between.

[0038] 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. Unless stated otherwise, the expression "up to" when referring to the compositional amount of an element means that element is optional and includes a zero percent composition of that particular element. Unless stated otherwise, all compositional percentages are in weight percent (wt.%).

[0039] As used herein, the meaning of "a," "an," and "the" includes singular and plural references unless the context clearly dictates otherwise.

[0040] In the following examples, aluminum alloy products and their components may be described in terms of their elemental composition in weight percent (wt.%). In each alloy, the remainder is aluminum, with a maximum wt.% of 0.15% for the sum of all impurities.

[0041] Incidental elements, such as grain refiners and deoxidizers, or other additives may be present in the invention and may add other characteristics on their own without departing from or significantly altering the alloy described herein or the characteristics of the alloy described herein.

[0042] Unavoidable impurities, including materials or elements may be present in an alloy in minor amounts due to inherent properties of aluminum or leaching from contact with processing equipment. Some alloys, as described, may contain no more than about 0.25 wt.% of any element besides the alloying elements, incidental elements, and unavoidable impurities.

Methods of Producing and Preparing the Alloys and Aluminum Alloy Products

[0043] FIG. 1 provides an overview of an example method of making an aluminum alloy product. The method of FIG. 1 begins at 105, where an aluminum alloy is cast to form a cast aluminum alloy product, such as an ingot or other cast product. The alloys described herein can be cast using any suitable casting method known to those of ordinary skill in the art. As a few non-limiting examples, the casting process can include a direct chill (DC) casting process 110, a fusion casting process 115, or a continuous casting (CC) process 120. The continuous casting process can use a system including a pair of moving opposed casting surfaces (e.g., moving opposed belts, rolls or blocks), a casting cavity between the pair of moving opposed casting surfaces, and a molten metal injector. The molten metal injector can have an end opening from which molten metal can exit the molten metal injector and be injected into the casting cavity.

[0044] A clad layer can be attached to a core layer to form a cladded product by any means known to persons of ordinary skill in the art. For example, a clad layer can be attached to a core layer by direct chill co-casting (i.e., fusion casting 115) as described in, for example, U.S. Patent Nos. 7,748,434 and 8,927,113, both of which are hereby incorporated by reference in their entireties; by hot and cold rolling a composite cast ingot as described in U.S. Patent No. 7,472,740, which is hereby incorporated by reference in its entirety; or by roll bonding to achieve metallurgical bonding between the core and the cladding. The initial dimensions and final dimensions of the clad aluminum alloy products described herein can be determined by the desired properties of the overall final product.

[0045] The cast aluminum alloy product is homogenized during a homogenization process 125 to form a homogenized aluminum alloy product. In a homogenization step, a cast product is heated to a temperature ranging from about 400 °C to about 565 °C. For example, the cast product can be heated to a temperature of 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, about 500 °C, about 510 °C, about 520 °C, about 530 °C, or about 540 °C up to 565 °C. The product is then allowed to soak (i.e., held at the indicated temperature) for a period of time to form a homogenized product. In some examples, the total time for the homogenization step, including the heating and soaking phases, can be up to 72 hours. For example, the product can be heated up to 500 °C and soaked, for a total time of up to 18 hours for the homogenization step. Optionally, the product can be heated to below 490 °C and soaked, for a total time of greater than 18 hours for the homogenization step. In some cases, the homogenization step comprises multiple processes. In some non-limiting examples, the homogenization step includes heating a cast product to a first temperature for a first period of time followed by heating to a second temperature for a second period of time. For example, a cast product can be heated to about 465 °C for about 3.5 hours and then heated to about 480 °C for about 6 hours. In some cases, the homogenization process 125 and casting process 105 are combined as casting with *in-situ* homogenization.

[0046] The homogenized aluminum alloy product is subjected to one or more roll bonding passes 130 and/or one or more hot rolling passes 135 to form a rolled aluminum alloy product, which may correspond to an aluminum alloy article, such as an aluminum alloy plate, an aluminum alloy shate, or an aluminum alloy sheet. A roll bonding process 130 can be carried out in different manners. For example, the roll bonding process 130 can include both hot rolling and cold rolling. Further, the roll bonding process 130 can be a one-step process or a multi-step process in which the material is gauged down during successive rolling steps. Separate rolling steps can optionally be separated by other processing steps, including, for example, annealing steps, cleaning steps, heating steps, cooling steps, and the like.

[0047] Prior to the start of hot rolling 135, the homogenized product can be allowed to cool to a temperature between 380 °C to 450 °C. For example, the homogenized product can be allowed to cool to a temperature of between 400 °C to 425 °C. The homogenized product can then be hot rolled at a temperature between 250 °C to 450 °C to form a hot rolled plate, a hot rolled shate or a hot rolled sheet having a gauge between 2 mm and 200 mm (e.g., 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, 50 mm, 55 mm, 60 mm, 65 mm, 70 mm, 75 mm, 80 mm, 85 mm, 90 mm, 95 mm, 100 mm, 110 mm, 120 mm, 130 mm, 140 mm, 150 mm, 160 mm, 170 mm, 180 mm, 190 mm, 200 mm, or anywhere in between).

[0048] Optionally, the cast product can be a continuously cast product that can be allowed to cool to a temperature between 300 °C to 450 °C. For example, the continuously cast product can be allowed to cool to a temperature of between 325 °C to 425 °C or from 350 °C to 400 °C. The continuously cast products can then be hot rolled at a temperature between 300 °C to 450 °C to form a hot rolled plate, a hot rolled shate or a hot rolled sheet having a gauge between 3 mm and 25 mm (e.g., 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9 mm, 10 mm, 15 mm, 20 mm, 25 mm, or anywhere in between).

[0049] Cast, homogenized, or hot-rolled products can be subjected to a break down process 140 or a break down and tandem process 145. Optionally, a cold rolling process 150 may be used after a hot rolling process 135, a break down process 140, or a break down and tandem process 145. The cold rolling process 150 can use cold rolling mills to cold roll the aluminum product into thinner products, such as a cold rolled sheet. The cold rolled product can have a gauge between about 0.1 to 7 mm, e.g., between about 0.7 to 6.5 mm. Optionally, the cold rolled product can have a gauge of 0.5 mm, 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm, 3.0 mm, 3.5 mm, 4.0 mm, 4.5 mm, 5.0 mm, 5.5 mm, 6.0 mm, 6.5 mm, 7.0 mm. The cold rolling 150 can be performed to result in a final gauge thickness that represents a gauge reduction of up to 95% (e.g., up to 10%, up to 20%, up to 30%, up to 40%, up to 50%, up to 55%, up to 60%, up to 70%, up to 75%, up to 80%, or up to 85%, or up to 90%, up to 95%, or up to 99% reduction) as compared to a gauge prior to the start of cold rolling 150.

[0050] Following cold rolling process 150, an intermediate annealing step 155 can be used. In some cases, cold rolling process 150 is not used and a product after a hot rolling process 135, a breakdown process 140, and/or a breakdown/tandem process 145 is subjected to intermediate annealing step 155. The intermediate annealing step 155 can be any suitable treatment which results in a recrystallized aluminum product. The intermediate annealing step 155 can comprise subjecting an unrecrystallized aluminum product to a heat treatment at a predefined temperature of less than or equal to 495 °C for a length of time less than or equal to 25 minutes to generate a recrystallized aluminum product. For example, the cast, homogenized, hot rolled, or cold rolled product can be heated to a temperature of up to 495 °C for a length of time up to 25 minutes as part of intermediate annealing step 155. In some examples, the temperature may be from about 300 °C to about 495 °C, such as from 300 °C to 305 °C, from 305 °C to 310 °C, from 310 °C to 315 °C, from 315 °C to 320 °C, from 320 °C to 325 °C, from 325 °C to 330 °C, from 330 °C to 335 °C, from 335 °C to 340 °C, from 340 °C to 345 °C, from 345 °C to 350 °C, from 350 °C to 355 °C, from 355 °C to 360 °C, from 360 °C to 365 °C, from 365 °C to 370 °C, from 370 °C to 375 °C, from 375 °C to 380 °C, from 380 °C to 385 °C, from 385 °C to 390 °C, from 390 °C to 395 °C, from 395 °C to 400 °C, from 400 °C to 405 °C, from 405 °C to 410 °C, from 410 °C to 415 °C, from 415 °C to 420 °C, from 420 °C to 425 °C, from 425 °C to 430 °C, from 430 °C to 435 °C, from 435 °C to 440 °C, from 440 °C to 445 °C, from 445 °C to 450 °C, from 450 °C to 455 °C, from 455 °C to 460 °C, from 460 °C to 465 °C, from 465 °C to 470 °C, from 470 °C to 475 °C, from 475 °C to 480 °C, from 480 °C to 485 °C, from 485 °C to 490 °C, from 490 °C to 495 °C, or from 490 °C to 495 °C. In some examples, the temperature may be from 320 °C to 495 °C, from 340 °C to 485 °C, from 350 °C to 475 °C, or from 370 °C to 475 °C. Any suitable temperature ramp rates may be used to heat up to and or cool down from the specified temperature. In some examples, the product is heated to the temperature for a length of time from about 0.1 seconds to about 25 minutes, such as from 0.1 seconds to 1 second, from 1 second to 2 seconds, from 2 seconds to 3 seconds, from 3 seconds to 4 seconds, from 4 seconds to 5 seconds, from 5 seconds to 10 seconds, from 10 seconds to 15 second, from 15 seconds to 30 seconds, from 30 seconds to 45 seconds, from 45 seconds to 60 seconds, from 60 seconds to 75 seconds, from 75 seconds to 90 seconds, from 90 seconds to 105 seconds, from 105 seconds to 2 minutes, from 2 minutes to 3 minutes, from 3 minutes to 4 minutes, from 4 minutes to 5 minutes, from 5 minutes to 10 minutes, from 10 minutes to 15 minutes, from 15 minutes to 20 minutes, or from 20 minutes to 25 minutes. In some cases, this may indicate that the temperature is held at or about a specified temperature or within 5 °C or within 10 °C of the specified temperature for the length of time. In some examples, the temperature or temperature range may be paired with a specific length of time or time range. For example, the temperature may be from 340 °C to 485 °C while the length of time is less than or equal to 10 minutes, the temperature may be from 350 °C to 475 °C while the length of time is less than 1 minute, or the temperature may be from 370 °C to 475 °C while the length of time is from 2 seconds to 35 seconds. Any variation or combination of the above-mentioned temperatures and lengths of time may be used, and certain alloys or end product configurations may benefit from a particular temperature and length of time combination or range of particular temperatures and lengths of time.

[0051] The intermediate annealing step 155 can include passing the cast, homogenized, or rolled product through a furnace at a speed from about 10 m/min to about 150 m/min, such as from 10 m/min to 15 m/min, from 15 m/min to 20 m/min, from 20 m/min to 25 m/min, from 25 m/min to 30 m/min, from 30 m/min to 40 m/min, from 40 m/min to 45 m/min, from 45 m/min to 50 m/min, from 50 m/min to 60 m/min, from 60 m/min to 70 m/min, from 70 m/min to 80 m/min, from 80 m/min to 90 m/min, from 90 m/min to 100 m/min, from 100 m/min to 110 m/min, from 110 m/min to 120 m/min, from 120 m/min to 130 m/min, from 130 m/min to 140 m/min. or from 140 m/min to 150 m/min. In some instances, the intermediate annealing step 155 can include heating the cast, homogenized, or rolled product by passing the product through a gas-fired furnace. In some instances, the intermediate annealing step 155 can include a magnetic heating unit with a heating rate of from 10 °C/s to 150 °C/s. Optionally, the intermediate annealing step 155 can include a quenching process (e.g., a water quench or an air quench) with a cooling rate of from 5 °C/s to 150 °C/s, or more, to return the product to ambient or room temperature. Cold rolling 160 the product after the intermediate annealing step 155 may result in an unrecrystallized aluminum product with deformed grains. Cold rolling 160 can be performed to create a final gauge thickness that represents a gauge reduction from 25% to 99% (e.g., from 25% to 30%, from 30% to 35%, from 35% to 40%, from 40% to 45%, from 45% to 50%, from 50% to 55%, from 55% to 60%, from 60% to 65%, from 65% to 70%, from 70% to 75%, from 75% to 80%, from 80% to 85%, from 85% to 90%, from 90% to 95%, or from 95% to 99% reduction) as compared to the gauge prior to cold rolling 160. In some specific examples, a cold rolling process may achieve a cold reduction from 55% to 75%, from 25% to 90%, from 45% to 95%, or from 60% to 99%.

[0052] Subsequently, the product can optionally undergo one or more solution heat treatment steps 165 to form a dual-recrystallized aluminum product 170. The solution heat treatment steps 165 can be any suitable treatment for the sheet which results in solutionizing of the soluble particles. As examples, the product can be heated to a peak metal temperature (PMT) of up to 590 °C (e.g., from 400 °C to 590 °C) and soaked for a period of time at the PMT to form a hot product. For example, the product can be soaked at 480 °C for a soak time of up to 30 minutes (e.g., 0 seconds, 60 seconds, 75 seconds, 90 seconds, 5 minutes, 10 minutes, 20 minutes, 25 minutes, or 30 minutes). After heating and soaking, the hot product is rapidly cooled at rates greater than 90 °C/s to a temperature between 500 °C and room temperature to form a heat-treated product.

[0053] After quenching, the heat-treated product can optionally undergo a pre-aging treatment by reheating before coiling. The pre-aging treatment can be performed at a temperature of from about 50 °C to about 125 °C for a period of time of up to 6 hours. For example, the pre-aging treatment can be performed at a temperature of about 50 °C, about 55 °C. about 60 °C, about 65 °C, about 70 °C, about 75 °C, about 80 °C, about 85 °C, about 90 °C, about 95 °C, about 100 °C, about 105 °C, about 110 °C, about 115 °C, about 120 °C, or about 125 °C. Optionally, the pre-aging treatment can be performed for about 30 minutes, about 1 hour, about 2 hours, about 3 hours, about 4 hours, about 5 hours, or about 6 hours. The pre-aging treatment can be carried out by passing the heat-treated product through a heating device, such as a device that emits radiant heat, convective heat, induction heat, infrared heat, or the like.

[0054] FIG. 2 provides a plot showing example temperatures of a cast metal product during various stages of a manufacturing process in accordance with various aspects of the present disclosure. As part of an initial casting stage 205, where molten metal is formed into an ingot, cast article, or other solid object or metal product, the molten metal may be cooled and/or solidified by a process involving quenching or cooling the metal by exposing the metal to water or an aqueous solution, such as in a direct chill casting process or in a continuous casting process that includes quenching immediately after casting.

[0055] Following the casting stage 205, the metal product may be subjected to a homogenization process 210, where the metal is heated to a temperature less than the melting or solidus temperature of the metal. Optionally, the metal product is heated to a temperature at which the base metal and any alloying elements form a solid solution.

[0056] Following the homogenization process 210, the metal product may be exposed to one or more processes that may, for example, form desirable microcrystalline structures within the metal product while elongating the metal product. Such processes may correspond to hot rolling 215 and/or cold rolling 220, for example, such as to form shates, plates, or sheets from a metal ingot or other cast article or metal product.

[0057] In some embodiments, exposing a metal product at an elevated temperature to a solution, such as water, an aqueous solution, or a gas-phase solution, in a quenching or cooling process may be used to reduce the temperature of the metal product to a temperature desirable or useful for a subsequent process. For example, exposing the metal product to water or an aqueous solution may be useful for cooling the metal product between hot rolling process 215 and subsequent processing. Tandem and/or breakdown processing is not shown in FIG. 2 but can be performed at any suitable temperature for such processes.

[0058] Following the hot rolling process 215 and/or the cold rolling process 220 (cold rolling process 220 may be optional), the metal product may be subjected to an intermediate annealing heat treatment process 225, where the metal product is heated to and held at a predefined temperature for a length of time less than or equal to an hour to generate at least partial recrystallization of the metal product. The metal product may be optionally subjected to an additional cold rolling process 230 after the intermediate annealing heat treatment process 225. Various different peak temperatures may be used for the intermediate annealing heat treatment process 225, as shown in FIG. 2, which may be dependent on the particular alloy of the metal product and/or the particular mechanical or physical properties desired for the final product, for example.

[0059] The metal product may then be subjected to a solution heat treatment process 235, where the temperature of the metal product is increased to a temperature above a threshold temperature, such as a temperature at which precipitated components in the metal product dissolve into a solid solution or a temperature at which recrystallization processes occur, and held at or above the threshold temperature for a period of time. At the end of the solution heat treatment process 235, the metal product may be subjected to a quenching process 240, where dissolved components are fixed into place by rapidly reducing the temperature of the metal by a quenching process. Such a quenching process 240 may involve exposing the metal product to a solution, such as a quench solution including water, an aqueous solution, or a gas or gas mixture.

[0060] In embodiments, the processes overviewed in FIG. 2 may be performed discretely or as part of one or more continuous processing lines where metal product may be transported as a coil, a film, or a web of material between processing stages. The metal product may be transported between stages by rolling the metal product, which may be under tension, over or between one or more rollers, or by transporting the metal product on one or more conveyors, for example. In addition, other stages not explicitly identified may be included before, between, and/or after any stage identified in FIG. 2. Other example stages include, but are not limited to, a tandem and/or breakdown stage, a washing stage, a chemical treatment stage, or a finishing stage. As an example, a finishing stage may correspond to a surface anodizing stage, a powder coating stage, a painting stage, a printing stage, and the like.

[0061] FIG. 3 provides an overview of an example method for producing a recrystallized aluminum product. At block 305, an unrecrystallized aluminum product is provided. Any desirable technique for producing the unrecrystallized aluminum product may be used, such as the casting, homogenization, hot rolling, or cold rolling steps described in FIGS. 1 and 2. The unrecrystallized aluminum product can have a thickness from about 1.0 mm to about 7.0 mm, such as from 1.0 mm to 1.2 mm, from 1.2 mm to 1.4 mm, from 1.4 mm to 1.6 mm, from 1.6 mm to 1.8 mm, from 1.8 mm to 2.0 mm, from 2.0 mm to 2.2 mm, from 2.2 mm to 2.4 mm, from 2.4 mm to 2.6 mm, from 2.6 mm to 2.8 mm, from 2.8 mm to 3.0 mm, from 3.0 mm to 3.2 mm, from 3.2 mm to 3.4 mm, from 3.4 mm to 3.6 mm, from 3.6 mm to 3.8 mm, from 3.8 mm to 3.0 mm, from 4.0 mm to 4.2 mm, from 4.2 mm to 4.4 mm, from 4.4 mm to 4.6 mm, from 4.6 mm to 4.8 mm, from 4.8 mm to 5.0 mm, from 5.0 mm to 5.2 mm, from 5.2 mm to 5.4 mm, from 5.4 mm to 5.6 mm, from 5.6 mm to 5.8 mm, from 5.8 mm to 6.0 mm, from 6.0 mm to 6.2 mm, from 6.2 mm to 6.4 mm, from 6.4 mm to 6.6 mm, from 6.6 mm to 6.8 mm, or from 6.8 mm to 7.0 mm. The unrecrystallized aluminum product may be a cold-rolled aluminum product and/or a hot-rolled aluminum product, for example.

[0062] At block 310, the unrecrystallized aluminum product is subjected to an annealing heat treatment at a predefined temperature of less than or equal to 495 °C for a length of time less than or equal to 25 minutes to generate a recrystallized aluminum product. The annealing heat treatment may involve using a magnetic heating process or passing the unrecrystallized aluminum product through a gas-fired furnace. The speed of the unrecrystallized aluminum product as it passes through the furnace can be from 10 m/min to 200 m/min. In one example, the annealing heat treatment occurs at a temperature of at most 350 °C for at most one minute. The recrystallized product may have a thickness from about 1.0 mm to about 7.0 mm (e.g., 1.0 mm, 1.5 mm, 2.0 mm, 2.2 mm, 2.5 mm, 3.0 mm, 3.5 mm, 4.0 mm, 4.5 mm, 5.0 mm, 5.5 mm, 6.0 mm, 6.5 mm, or 7.0 mm.

[0063] At block 315, the recrystallized aluminum product is subjected to a cold rolling process to generate a cold rolled aluminum product. The cold rolling process can result in a cold reduction from 25% to 99%, such as from 25% to 90%, from 45% to 95%, or from 55% to 75%, or from 60% to 99%.

[0064] At block 320, the cold rolled product is subjected to a solution heat treatment to generate a dual-recrystallized aluminum product. The dual-recrystallized aluminum product generated by the intermediate annealing heat treatment and the solution heat treatment may exhibit reduced roping and improved physical properties, such as improved bending and elongation properties. For example, roping may be characterized by a surface arithmetic mean height (Sa). In some examples, the recrystallized aluminum product can optionally exhibit a surface arithmetic mean height (Sa) of at most 0.50 μm or from 0.01 μm to 50 μm, such as from 0.01 μm to 0.05 μm, from 0.05 μm to 0.10 μm, from 0.10 μm to 0.50 μm, from 0.50 μm to 1.0 μm, from 1.0 μm to 5.0 μm, from 5.0 μm to 10 μm, from 10 μm to 15 μm, from 15 μm to 20 μm, from 20 μm to 25 μm, from 25 μm to 30 μm, from 30 μm to 35 μm, from 35 μm to 40 μm, from 40 μm to 45 μm, or from 45 μm to 50 μm. Additionally, the recrystallized aluminum product may optionally exhibit an f10% bending value of at most 0.55 in a transverse direction, such as from 0.01 to 0.55 in a transverse direction, or an f15% bending value of at most 0.70 in a transverse direction, such as from 0.01 to 0.70 in a transverse direction. In some examples, the f10% bending value in a transverse direction may be from 0.01 to 0.05, from 0.05 to 0.10, from 0.10 to 0.15, from 0.15 to 0.20, from 0.20 to 0.25, from 0.25 to 0.30, from 0.30 to 0.35, from 0.35 to 0.40, from 0.40 to 0.45, from 0.45 to 0.50, or from 0.50 to 0.55. In some examples, the f15% bending value in a transverse direction may be from 0.01 to 0.05, from 0.05 to 0.10, from 0.10 to 0.15, from 0.15 to 0.20, from 0.20 to 0.25, from 0.25 to 0.30, from 0.30 to 0.35, from 0.35 to 0.40, from 0.40 to 0.45, from 0.45 to 0.50, from 0.50 to 0.55, from 0.55 to 0.60, from 0.60 to 0.65, or from 0.65 to 0.70. The f-bending factor may be measured according to ASTM E290, where $f = r/t$ for a given pre-straining, with r being the lowest radius of the bend without any surface visible cracks to an unaided eye and t being the sheet thickness after the straining. For example, f10% is the bending factor after pre-straining of 10% in the transverse direction. The recrystallized product may additionally or alternatively exhibit a uniform elongation of at least 21%, such as from 21% to 99% or more. The recrystallized product may additionally or alternatively exhibit a conductivity from 25 mΩ/m to 40 mΩ/m. The recrystallized product can include an average precipitate size from 0.05 μm to 0.5 μm, with undissolved precipitates occupying an area fraction from 0% to 1% of the recrystallized product, and/or microvoids occupying an area fraction from 0% to 0.3% of the recrystallized product.

Recrystallized Aluminum Alloy Products

[0065] FIG. 4A and FIG. 4B provide schematic illustrations of an exemplary unrecrystallized product 410 and an exemplary recrystallized product 420. The unrecrystallized product 410 may be a cast, homogenized, hot-rolled, and/or cold-rolled aluminum product, for example. The recrystallized product 420 can be the unrecrystallized product 410 subsequent to an annealing heat treatment, as described herein, such as heated to and held at a temperature below 495 °C for at most 25 minutes. In the unrecrystallized product 410, the grains 412 have an elongated character (e.g., length longer than width). In contrast, in recrystallized product 420, the grains 432 have a more uniform character (e.g., length and width relatively close in magnitude to one another). It will be appreciated that the illustrations of unrecrystallized product 410 and recrystallized product 420 are merely for purposes of illustration and are not to scale.

[0066] As described previously, the recrystallized product 420 may processed further to generate an aluminum alloy product that exhibits reduced roping and improved bending and elongation properties, particularly when compared to another aluminum alloy product that is subjected to the same processing conditions except that it is not subjected to the short-duration, low-temperature inter-annealing heat treatment described above, such as a low temperature of 400 °C or 350 °C for a period of up to 25 minutes or 1 minute.

[0067] In some cases, precipitates present in the product can grow during the recrystallization achieved by the short-duration, low-temperature annealing heat treatment, due to increased diffusion of component elements at the elevated temperature conditions of the short-duration, low-temperature annealing heat treatment process. In some cases, small precipitates present in the product can be dissolved during the recrystallization achieved by the short-duration, low-temperature annealing heat treatment. The presence of undissolved precipitates may be undesirable, and so subsequent continuous annealing and solution heat treatment processing may be warranted. In some extreme cases, precipitates present in the product can grow to sizes large enough that they may not completely dissolve during a subsequent continuous annealing and solution heat treatment processing, and so it may be desirable to achieve a balance between the amount of recrystallization achieved and the average size of precipitates upon conclusion of the short-duration, low-temperature annealing heat treatment process.

Methods of Using the Disclosed Aluminum Alloy Products

[0068] The aluminum alloy products described herein can be used in automotive applications and other transportation applications, including aircraft and railway applications. For example, the disclosed aluminum alloy products can be used to prepare automotive structural parts, such as bumpers, side beams, roof beams, cross beams, pillar reinforcements (e.g., A-pillars, B-pillars, and C-pillars), inner panels, outer panels, side panels, inner hoods, outer hoods, or trunk lid panels. The aluminum alloy products and methods described herein can also be used in aircraft or railway vehicle applications, to prepare, for example, external and internal panels.

[0069] The aluminum alloy products and methods described herein can also be used in electronics applications. For example, the aluminum alloy products and methods described herein can be used to prepare housings for electronic devices, including mobile phones and tablet computers. In some examples, the aluminum alloy products can be used to prepare housings for the outer casing of mobile phones (e.g., smart phones), tablet bottom chassis, and other portable electronics.

Methods of Treating Metals and Metal Alloys

[0070] Described herein are methods of treating metals and metal alloys, including aluminum, aluminum alloys, magnesium, magnesium alloys, magnesium composites, and steel, among others, and the resultant treated metals and metal alloys. In some examples, the metals for use in the methods described herein include aluminum alloys, for example, 1xxx series aluminum alloys, 2xxx series aluminum alloys, 3xxx series aluminum alloys, 4xxx series aluminum alloys, 5xxx series aluminum alloys, 6xxx series aluminum alloys, 7xxx series aluminum alloys, or 8xxx series aluminum alloys. In some examples, the materials for use in the methods described herein include non-ferrous materials, including aluminum, aluminum alloys, magnesium, magnesium-based materials, magnesium alloys, magnesium composites, titanium, titanium-based materials, titanium alloys, copper, copper-based materials, composites, sheets used in composites, or any other suitable metal, non-metal or combination of materials. Monolithic as well as non-monolithic, such as roll-bonded materials, cladded alloys, clad layers, composite materials, such as but not limited to carbon fiber-containing materials, or various other materials are also useful with the methods described herein. In some examples, aluminum alloys containing iron are useful with the methods described herein.

[0071] By way of non-limiting example, exemplary 1xxx series aluminum alloys for use in the methods described herein can include AA1100, AA1100A, AA1200, AA1200A, AA1300, AA1110, AA1120, AA1230, AA1230A, AA1235, AA1435, AA1145, AA1345, AA1445, AA1150, AA1350, AA1350A, AA1450, AA1370, AA1275, AA1185, AA1285, AA1385, AA1188, AA1190, AA1290, AA1193, AA1198, or AA1199.

[0072] Non-limiting exemplary 2xxx series aluminum alloys for use in the methods described herein can include AA2001, AA2002, AA2004, AA2005, AA2006, AA2007, AA2007A, AA2007B, AA2008, AA2009, AA2010, AA2011, AA2011A, AA2111, AA2111A, AA2111B, AA2012, AA2013, AA2014, AA2014A, AA2214, AA2015, AA2016, AA2017, AA2017A, AA2117, AA2018, AA2218, AA2618, AA2618A, AA2219, AA2319, AA2419, AA2519, AA2021, AA2022, AA2023, AA2024, AA2024A, AA2124, AA2224, AA2224A, AA2324, AA2424, AA2524, AA2624, AA2724, AA2824, AA2025, AA2026, AA2027, AA2028, AA2028A, AA2028B, AA2028C, AA2029, AA2030, AA2031, AA2032, AA2034, AA2036, AA2037, AA2038, AA2039, AA2139, AA2040, AA2041, AA2044, AA2045, AA2050, AA2055, AA2056, AA2060, AA2065, AA2070, AA2076, AA2090, AA2091, AA2094, AA2095, AA2195, AA2295, AA2196, AA2296, AA2097, AA2197, AA2297, AA2397, AA2098, AA2198, AA2099, or AA2199.

[0073] Non-limiting exemplary 3xxx series aluminum alloys for use in the methods described herein can include AA3002, AA3102, AA3003, AA3103, AA3103A, AA3103B, AA3203, AA3403, AA3004, AA3004A, AA3104, AA3204, AA3304, AA3005, AA3005A, AA3105, AA3105A, AA3105B, AA3007, AA3107, AA3207, AA3207A, AA3307, AA3009, AA3010, AA3110, AA3011, AA3012, AA3012A, AA3013, AA3014, AA3015, AA3016, AA3017, AA3019, AA3020, AA3021, AA3025, AA3026, AA3030, AA3130, or AA3065.

[0074] Non-limiting exemplary 4xxx series aluminum alloys for use in the methods described herein can include AA4004, AA4104, AA4006, AA4007, AA4008, AA4009, AA4010, AA4013, AA4014, AA4015, AA4015A, AA4115, AA4016, AA4017, AA4018, AA4019, AA4020, AA4021, AA4026, AA4032, AA4043, AA4043A, AA4143, AA4343, AA4643, AA4943, AA4044, AA4045, AA4145, AA4145A, AA4046, AA4047, AA4047A, or AA4147.

[0075] Non-limiting exemplary 5xxx series aluminum alloys for use in the methods described herein product can include AA5182, AA5183, AA5005, AA5005A, AA5205, AA5305, AA5505, AA5605, AA5006, AA5106, AA5010, AA5110, AA5110A, AA5210, AA5310, AA5016, AA5017, AA5018, AA5018A, AA5019, AA5019A, AA5119, AA5119A, AA5021, AA5022, AA5023, AA5024, AA5026, AA5027, AA5028, AA5040, AA5140, AA5041, AA5042, AA5043, AA5049, AA5149, AA5249, AA5349, AA5449, AA5449A, AA5050, AA5050A, AA5050C, AA5150, AA5051, AA5051A, AA5151, AA5251, AA5251A, AA5351, AA5451, AA5052, AA5252, AA5352, AA5154, AA5154A, AA5154B, AA5154C, AA5254, AA5354, AA5454, AA5554, AA5654, AA5654A, AA5754, AA5854, AA5954, AA5056, AA5356, AA5356A, AA5456, AA5456A, AA5456B, AA5556, AA5556A, AA5556B, AA5556C, AA5257, AA5457, AA5557, AA5657, AA5058, AA5059, AA5070, AA5180, AA5180A, AA5082, AA5182, AA5083, AA5183, AA5183A, AA5283, AA5283A, AA5283B, AA5383, AA5483, AA5086, AA5186, AA5087, AA5187, or AA5088.

[0076] Non-limiting exemplary 6xxx series aluminum alloys for use in the methods described herein can include AA6101, AA6101A, AA6101B, AA6201, AA6201A, AA6401, AA6501, AA6002, AA6003, AA6103, AA6005, AA6005A, AA6005B, AA6005C, AA6105, AA6205, AA6305, AA6006, AA6106, AA6206, AA6306, AA6008, AA6009, AA6010, AA6110, AA6110A, AA6011, AA6111, AA6012, AA6012A, AA6013, AA6113, AA6014, AA6015, AA6016, AA6016A, AA6116, AA6018, AA6019, AA6020, AA6021, AA6022, AA6023, AA6024, AA6025, AA6026, AA6027, AA6028, AA6031, AA6032, AA6033, AA6040, AA6041, AA6042, AA6043, AA6151, AA6351, AA6351A, AA6451, AA6951, AA6053, AA6055, AA6056, AA6156, AA6060, AA6160, AA6260, AA6360, AA6460, AA6460B, AA6560, AA6660, AA6061, AA6061A, AA6261, AA6361, AA6162, AA6262, AA6262A, AA6063, AA6063A, AA6463, AA6463A, AA6763, AA6963, AA6064, AA6064A, AA6065, AA6066, AA6068, AA6069, AA6070, AA6081, AA6181, AA6181A, AA6082, AA6082A, AA6182, AA6091, or AA6092.

[0077] Non-limiting exemplary 7xxx series aluminum alloys for use in the methods described herein can include AA7011, AA7019, AA7020, AA7021, AA7039, AA7072, AA7075, AA7085, AA7108, AA7108A, AA7015, AA7017, AA7018, AA7019A, AA7024, AA7025, AA7028, AA7030, AA7031, AA7033, AA7035, AA7035A, AA7046, AA7046A, AA7003, AA7004, AA7005, AA7009, AA7010, AA7011, AA7012, AA7014, AA7016, AA7116, AA7122, AA7023, AA7026, AA7029, AA7129, AA7229, AA7032, AA7033, AA7034, AA7036, AA7136, AA7037, AA7040, AA7140, AA7041, AA7049, AA7049A,

AA7149,7204, AA7249, AA7349, AA7449, AA7050, AA7050A, AA7150, AA7250, AA7055, AA7155, AA7255, AA7056, AA7060, AA7064, AA7065, AA7068, AA7168, AA7175, AA7475, AA7076, AA7178, AA7278, AA7278A, AA7081, AA7181, AA7185, AA7090, AA7093, AA7095, or AA7099.

[0078] Non-limiting exemplary 8xxx series aluminum alloys for use in the methods described herein can include AA8005, AA8006, AA8007, AA8008, AA8010, AA8011, AA8011A, AA8111, AA8211, AA8112, AA8014, AA8015, AA8016, AA8017, AA8018, AA8019, AA8021, AA8021A, AA8021B, AA8022, AA8023, AA8024, AA8025, AA8026, AA8030, AA8130, AA8040, AA8050, AA8150, AA8076, AA8076A, AA8176, AA8077, AA8177, AA8079, AA8090, AA8091, or AA8093.

[0079] The examples disclosed herein will serve to further illustrate aspects of the invention without, at the same time, however, constituting any limitation thereof. On the contrary, it is to be clearly understood that resort may be had to various embodiments, modifications and equivalents thereof which, after reading the description herein, may suggest themselves to those skilled in the art without departing from the spirit of the invention. The examples and embodiments described herein may also make use of conventional procedures, unless otherwise stated. Some of the procedures are described herein for illustrative purposes.

EXAMPLE 1

[0080] Ten alloys were prepared for evaluating properties of aluminum alloy sheet metal products after a short-duration low-temperature annealing heat treatment compared to other aluminum sheet metal products. Table 1 shows the alloys, the final thickness of the aluminum sheet metal products, and the natural aging duration of the aluminum sheet metal products. Table 2 shows the alloy compositions for the aluminum sheet metal products. Comparison Alloys 1 and 2 (CA1 and CA2) were produced by casting, homogenizing, hot rolling, and cold rolling. Comparison Alloys 3 and 4 (CA3 and CA4) were produced similar to Comparison Alloys 1 and 2, with two conventional solution heat treatments after the cold rolling steps. Variant A, Variant B, Variant C, Variant D, Variant E, and Variant F were aluminum alloys produced with a low temperature inter-annealing heat treatment (e.g., process 155 referred to with respect to FIG. 1) after an initial cold rolling step, followed by additional cold-rolling and a conventional solution heat treatment (e.g., process 165 referred to with respect to FIG. 1). Variant D, Variant E, and Variant F were the same aluminum alloys that were produced with varying lengths of the inter-annealing heat treatment. The inter-annealing heat treatment of Variant D was fifteen seconds, the inter-annealing heat treatment of Variant E was twenty-five seconds, and the inter-annealing heat treatment of Variant F was thirty-five seconds.

Name	Thickness	Natural Aging Days
Comparison Alloy 1	1.15 mm	23
Comparison Alloy 2	1.02 mm	26
Comparison Alloy 3	1.04 mm	30
Comparison Alloy 4	1.1 mm	65
Variant A	1.02 mm	12
Variant B	1.02 mm	12
Variant C	1.02 mm	12
Variant D	1.02 mm	25
Variant E	1.02 mm	25
Variant F	1.02 mm	25

Table 1

Name	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V
Comparison Alloy 1	1.35	0.1722	0.1304	0.08	0.3009	0.0106	0.0082	0.0193	0.0216
Comparison Alloy 2	0.99	0.235	0.102	0.16	0.417	0.0345	0.01	0.031	0.017
Comparison Alloy 3	1.12	0.20	0.06	0.06	0.41	0.0090	0.006	0.022	0.025
Comparison Alloy 4	1.36	0.215	0.128	0.085	0.32	0.01	0.009	0.018	0.0224
Variant A	0.98	0.19	0.019	0.0077	0.5	0.046	0.006	0.021	0.0235
Variant B	1.33	0.194	0.114	0.08	0.3114	0.0109	0.0096	0.021	0.026
Variant C	0.99	0.235	0.102	0.16	0.417	0.0345	0.01	0.031	0.017
Variant D	1.27	0.17	0.116	0.08	0.3	0.0097	0.0032	0.0224	0.02
Variant E	1.27	0.17	0.116	0.08	0.3	0.0097	0.0032	0.0224	0.02
Variant F	1.27	0.17	0.116	0.08	0.3	0.0097	0.0032	0.0224	0.02

Table 2

EXAMPLE 2

[0081] Strength properties of various alloys described in Example 1 were tested and are summarized in FIG. 5A, FIG. 5B, FIG. 5C, FIG. 5D, FIG. 5E, and FIG. 5F. Shown are the yield strength (FIG. 5A and FIG. 5B), ultimate tensile strength (FIG. 5C and FIG. 5D), and a ratio of the yield strength to the ultimate tensile strength (FIG. 5E and FIG. 5F), where L, T, and D correspond to measurements along the longitudinal, transverse and diagonal directions, respectively. Variant A, Variant B, Variant C, Variant D, Variant E, and Variant F exhibit similar properties to each other in the longitudinal, transverse, and diagonal directions. Each of Variant A, Variant B, Variant C, Variant E, and Variant F exhibit improved strength properties compared to Comparison Alloy 1 and comparable strength properties to Comparison Alloy 2, Comparison Alloy 3, and Comparison Alloy 4.

EXAMPLE 3

[0082] Elongation properties of various alloys described in Example 1 were tested and are summarized in FIG. 6A, FIG. 6B, FIG. 6C, FIG. 6D, FIG. 6E, FIG. 6F, FIG. 6G, and FIG. 6H. The uniform elongation (FIG. 6A and FIG. 6B), total elongation (FIG. 6C and FIG. 6D), strain-hardening exponent for 5% strain (FIG. 6E and FIG. 6F), and strain-hardening exponent for 10-20% strain (FIG. 6G and FIG. 6H) were evaluated for each alloy. Each of Variant A, Variant B, Variant C, Variant D, Variant E, and Variant F exhibit a uniform elongation of at least 21% in the longitudinal, transverse, and diagonal directions. The variants outperform Comparison Alloy 2 and Comparison Alloy 4 for each of the elongation properties and exhibit comparable properties to Comparison Alloy 3. Variant B, Variant D, Variant E, and Variant F exhibit comparable results to those of Comparison Alloy 1.

EXAMPLE 4

[0083] Additional strain, bending, and surface characteristics of various alloys described in Example 1 were tested and are shown in FIG. 7A, FIG. 7B, FIG. 7C, FIG. 7D, FIG. 7E, FIG. 7F, FIG. 7G, and FIG. 8. Bending values for a pre-straining of 10% (FIG. 7A and FIG. 7B) and a pre-straining of 15% (FIG. 7C and FIG. 7D) were evaluated, as well as a Lankford ratio at 10% strain (8% to 12%) (FIG. 7E and FIG. 7F). In the transverse direction, Variant A, Variant B, Variant C, Variant D, Variant E, and Variant F each outperformed Comparison Alloy 1, Comparison Alloy 2, Comparison Alloy 3, and Comparison Alloy 4 for both the bending tests. To characterize roping of the alloys, arithmetic mean height, Sa, and surface profile analysis using a fast Fourier transform (FFT) method were also evaluated (FIG. 7G).

FFT can be compared to the roping value measurement according to the VDA 239-400 recommendation (RK). Variant A, Variant B, and Variant C exhibit less roping than Comparison Alloy 1 and Comparison Alloy 2 and are comparable to Comparison Alloy 3. The surface profile was evaluated for Comparison Alloy 1, Comparison Alloy 4, and Variant D (FIG. 8). Comparison Alloy 4 outperforms the other two alloys, with Variant D outperforming Comparison Alloy 1.

EXAMPLE 5

[0084] Grain and precipitate characteristics of the Comparison Alloy 1, Comparison Alloy 2, Variant B, and Variant C alloys were evaluated. FIG. 9A shows an example micrograph image of a hot-rolled aluminum product, showing an elongated grain structure. After cold rolling to 2.2 mm, the grains are further elongated, as shown in the top panel of FIG. 9B. The bottom panel of FIG. 9B highlights precipitates present in the aluminum matrix, and shows many fine precipitates, though some larger precipitates can be seen. After cold rolling, the aluminum product is subjected to a short-duration, low-temperature annealing heat treatment where it is heated to 350 °C for five seconds, allowing the metal to recrystallize, at least in part. FIG. 9C shows a recrystallized grain structure in the top panel; the bottom panel shows many of the small precipitates are dissolved, but some of the precipitates grow in size. FIG. 10A shows a cross section of a recrystallized grain structure of Comparison Alloy 1, Variant B, and Variant D. FIG. 10B shows the surface of the recrystallized grain structure of Comparison Alloy 1, Variant B, and Variant D. Comparison Alloy 1 has finer grains than Variant B and Variant D, with Variant D having finer grains than Variant B. FIG. 11A shows a bar graph indicating an area fraction of undissolved precipitates and equivalent circular diameter (ECD) of undissolved precipitates, with variant C showing the smallest area fraction of undissolved precipitates. FIG. 11B shows a bar graph indicating the conductivity of each alloy, which can provide an indication of the amount of dissolved precipitates, with Variant B and Variant C both exhibit lower conductivities than Comparison Alloy 2 and Comparison Alloy 1, potentially indicating at least some of the precipitates dissolve during the short-duration, low-temperature annealing heat treatment.

EXAMPLE 6

[0085] Micrograph images of samples of the Comparison Alloy 1, Comparison Alloy 2, Variant B, Variant C, and Variant D alloys were obtained and are shown in FIG. 12. The images show the microstructure of the five alloys, where the small, dark spots within the grains correspond to undissolved precipitates and the white spots surrounding and adjacent to the undissolved precipitates corresponding to microvoids. FIG. 13A provides a bar graph showing an area fraction of the microvoids and an ECD of the microvoids. FIG. 13 B provides a bar graph showing an area fraction of undissolved precipitates and an ECD of undissolved precipitates. Variant B and Variant C showed less and smaller microvoids than Comparison Alloy 2 and Comparison Alloy 1. FIG. 14 provides a bar graph showing microvoids and undissolved precipitates in Comparison Alloy 1, Variant B, and Variant D. Variant B and Variant D both show less microvoids and undissolved precipitates than Comparison Alloy 1.

ILLUSTRATIVE ASPECTS

[0086] As used below, any reference to a series of aspects (e.g., “Aspects 1-4”) or non-enumerated group of aspects (e.g., “any previous or subsequent aspect”) is to be understood as a reference to each of those aspects disjunctively (e.g., “Aspects 1-4” is to be understood as “Aspects 1, 2, 3, or 4 ”).

[0087] Aspect 1 is a method, comprising: providing an unrecrystallized aluminum product; subjecting the unrecrystallized aluminum product to an intermediate annealing heat treatment at a predefined temperature of less than or equal to 495 °C for a length of time less than or equal to 25 minutes to generate a recrystallized aluminum product; subjecting the recrystallized aluminum product to a cold rolling process to generate a cold rolled aluminum product; and subjecting the cold rolled aluminum product to a solution heat treatment to generate a dual-recrystallized aluminum product.

[0088] Aspect 2 is the method of any previous or subsequent aspect, wherein the predefined temperature is from 280 °C to 495 °C or from 320 °C to 495 °C.

[0089] Aspect 3 is the method of any previous or subsequent aspect, wherein the predefined temperature is from 300 °C to 430 °C and the length of time is less than or equal to 10 minutes, or wherein the predefined temperature is from 340 °C to 485 °C and the length of time is less than or equal to 10 minutes.

[0090] Aspect 4 is the method of any previous or subsequent aspect, wherein the predefined temperature is from 330 °C to 400 °C and the length of time is less than 1 minute, or wherein the predefined temperature is from 350 °C to 475 °C and the length of time is less than 1 minute.

[0091] Aspect 5 is the method of any previous or subsequent aspect, wherein the predefined temperature is from 345 °C to 385 °C and the length of time is from 2 seconds to 35 seconds, or wherein the predefined temperature is from 370 °C to 470 °C and the length of time is from 2 seconds to 35 seconds.

[0092] Aspect 6 is the method of any previous or subsequent aspect, wherein the cold rolling process achieves a cold reduction from 55% to 75%.

[0093] Aspect 7 is the method of any previous or subsequent aspect, wherein the cold rolling process achieves a cold reduction from 25% to 90%.

[0094] Aspect 8 is the method of any previous or subsequent aspect, wherein the cold rolling process achieves a cold reduction from 45% to 95%.

[0095] Aspect 9 is the method of any previous or subsequent aspect, wherein the cold rolling process achieves a cold reduction from 60% to 99%.

[0096] Aspect 10 is the method of any previous or subsequent aspect, wherein the dual-recrystallized aluminum product exhibits a surface arithmetical mean height (Sa) of at most 0.50 μm.

[0097] Aspect 11 is the method of any previous or subsequent aspect, wherein the dual-recrystallized aluminum product exhibits an f10% bending value of at most 0.55 in a transverse direction.

[0098] Aspect 12 is the method of any previous or subsequent aspect, wherein the dual-recrystallized aluminum product exhibits an f15% bending value of at most 0.70 in a transverse direction.

[0099] Aspect 13 is the method of any previous or subsequent aspect, wherein the dual-recrystallized aluminum product exhibits a uniform elongation of at least 21%.

[0100] Aspect 14 is the method of any previous or subsequent aspect, wherein a thickness of the dual-recrystallized aluminum product is from 1.00 mm to 3.5 mm.

[0101] Aspect 15 is the method of any previous or subsequent aspect, wherein the recrystallized aluminum product comprises an average precipitate size of from 0.05 μm to 0.5 μm.

[0102] Aspect 16 is the method of any previous or subsequent aspect, wherein undissolved precipitates occupy an area fraction of from 0% to 1% of the recrystallized aluminum product.

[0103] Aspect 17 is the method of any previous or subsequent aspect, wherein microvoids occupy an area fraction of from 0% to 0.3% of the recrystallized aluminum product.

[0104] Aspect 18 is the method of any previous or subsequent aspect, wherein the recrystallized aluminum product exhibits a conductivity of from 25 mΩ/m to 40 mΩ/m.

[0105] Aspect 19 is the method of any previous or subsequent aspect, wherein the predefined temperature is at most 350 °C.

[0106] Aspect 20 is the method of any previous or subsequent aspect, wherein the length of time is at most five minutes.

[0107] Aspect 21 is the method of any previous or subsequent aspect, wherein the length of time is at most one minute.

[0108] Aspect 22 is the method of any previous or subsequent aspect, wherein the intermediate annealing heat treatment comprises passing the unrecrystallized aluminum product through a furnace at a speed of from 10 m/min to 200 m/min.

[0109] Aspect 23 is the method of any previous or subsequent aspect, wherein the intermediate annealing heat treatment comprises heating the unrecrystallized aluminum product using a magnetic heating process.

[0110] Aspect 24 is the method of any previous or subsequent aspect, wherein the intermediate annealing heat treatment comprises heating the unrecrystallized aluminum product by passing through a gas-fired furnace.

[0111] Aspect 25 is the method of any previous or subsequent aspect, wherein the unrecrystallized aluminum product comprises a 6xxx series aluminum alloy.

[0112] Aspect 26 is the method of any previous or subsequent aspect, wherein the unrecrystallized aluminum product comprises a 7xxx series aluminum alloy.

[0113] Aspect 27 is a rolled aluminum alloy product comprising: a 6xxx series aluminum alloy or a 7xxx series aluminum alloy, wherein an Sa of the 6xxx series aluminum alloy or the 7xxx series aluminum alloy is at most 0.50 µm; wherein a thickness of the rolled aluminum alloy product is from 1.00 mm to 3.5 mm; and wherein undissolved precipitates occupy an area fraction of from 0% to 1% of the rolled aluminum product.

[0114] Aspect 28 is the rolled aluminum alloy product of any previous or subsequent aspect, wherein the rolled aluminum product exhibits a conductivity of from 25 mΩ/m to 40 mΩ/m.

[0115] Aspect 29 is the rolled aluminum alloy product of any previous or subsequent aspect, wherein the rolled aluminum product comprises an average precipitate size of from 0.05 µm to 0.50 µm.

[0116] Aspect 30 is the rolled aluminum alloy product of any previous or subsequent aspect, wherein microvoids occupy an area fraction of from 0% to 0.3% of the rolled aluminum alloy product.

[0117] All patents and publications cited herein are incorporated by reference in their entirety. The foregoing description of the embodiments, including illustrated embodiments, has been presented only for the purpose of illustration and description and is not intended to be exhaustive or limiting to the precise forms disclosed. Numerous modifications, adaptations, and uses thereof will be apparent to those skilled in the art.

WHAT IS CLAIMED IS:

1. A method comprising:

providing an unrecrystallized aluminum product;

subjecting the unrecrystallized aluminum product to an intermediate annealing heat treatment at a predefined temperature of less than or equal to 495 °C for a length of time less than or equal to 25 minutes to generate a recrystallized aluminum product;

subjecting the recrystallized aluminum product to a cold rolling process to generate a cold rolled aluminum product; and

subjecting the cold rolled aluminum product to a solution heat treatment to generate a dual-recrystallized aluminum product.

2. The method of claim 1, wherein the predefined temperature is from 320 °C to 495 °C.

3. The method of claim 1, wherein the predefined temperature is from 340 °C to 485 °C and the length of time is less than or equal to 10 minutes.

4. The method of claim 1, wherein the predefined temperature is from 350 °C to 475 °C and the length of time is less than 1 minute.

5. The method of claim 1, wherein the predefined temperature is from 370 °C to 470 °C and the length of time is from 2 seconds to 35 seconds.

6. The method of claim 1, wherein the cold rolling process achieves a cold reduction from 55% to 75%.

7. The method of claim 1, wherein the cold rolling process achieves a cold reduction from 25% to 90%.

8. The method of claim 1, wherein the cold rolling process achieves a cold reduction from 45% to 95%.

9. The method of claim 1, wherein the cold rolling process achieves a cold reduction from 60% to 99%.

10. The method of claim 1, wherein the dual-recrystallized aluminum product exhibits a surface arithmetical mean height (Sa) of at most 0.50 µm.

11. The method of claim 1, wherein the dual-recrystallized aluminum product exhibits an f10% bending value of at most 0.55 in a transverse direction.

12. The method of claim 1, wherein the dual-recrystallized aluminum product exhibits an f15% bending value of at most 0.70 in a transverse direction.

13. The method of claim 1, wherein the dual-recrystallized aluminum product exhibits a uniform elongation of at least 21%.

14. The method of claim 1, wherein a thickness of the dual-recrystallized aluminum product is from 1.00 mm to 3.5 mm.

15. The method of claim 1, wherein the dual-recrystallized aluminum product comprises an average precipitate size of from 0.05 µm to 0.5 µm.

16. The method of claim 1, wherein undissolved precipitates occupy an area fraction of from 0% to 1% of the dual-recrystallized aluminum product.

17. The method of claim 1, wherein microvoids occupy an area fraction of from 0% to 0.3% of the dual-recrystallized aluminum product.

18. The method of claim 1, wherein the dual-recrystallized aluminum product exhibits a conductivity of from 25 mΩ/m to 40 mΩ/m.

19. The method of claim 1, wherein the predefined temperature is at most 350 °C.

20. The method of claim 1, wherein the length of time is at most five minutes.

21. The method of claim 1, wherein the length of time is at most one minute.

22. The method of claim 1, wherein the intermediate annealing heat treatment comprises passing the unrecrystallized aluminum product through a furnace at a speed of from 10 m/min to 200 m/min.

23. The method of claim 1, wherein the intermediate annealing heat treatment comprises heating the unrecrystallized aluminum product using a magnetic heating process.

24. The method of claim 1, wherein the intermediate annealing heat treatment comprises heating the unrecrystallized aluminum product by passing through a gas-fired furnace.

25. The method of claim 1, wherein the unrecrystallized aluminum product comprises a 6xxx series aluminum alloy.

26. The method of claim 1, wherein the unrecrystallized aluminum product comprises a 7xxx series aluminum alloy.

27. A rolled aluminum alloy product comprising:

a 6xxx series aluminum alloy or a 7xxx series aluminum alloy, wherein an Sa of the 6xxx series aluminum alloy or the 7xxx series aluminum alloy is at most 0.50 μm;

wherein a thickness of the rolled aluminum alloy product is from 1.00 mm to 3.5 mm; and

wherein undissolved precipitates occupy an area fraction of from 0% to 1% of the rolled aluminum alloy product.

28. The rolled aluminum alloy product of claim 27, wherein the rolled aluminum alloy product exhibits a conductivity of from 25 mΩ/m to 40 mΩ/m.

29. The rolled aluminum alloy product of claim 27, wherein the rolled aluminum alloy product comprises an average precipitate size of from 0.05 μm to 0.5 μm.

30. The rolled aluminum alloy product of claim 27, wherein microvoids occupy an area fraction of from 0% to 0.3% of the rolled aluminum alloy product.

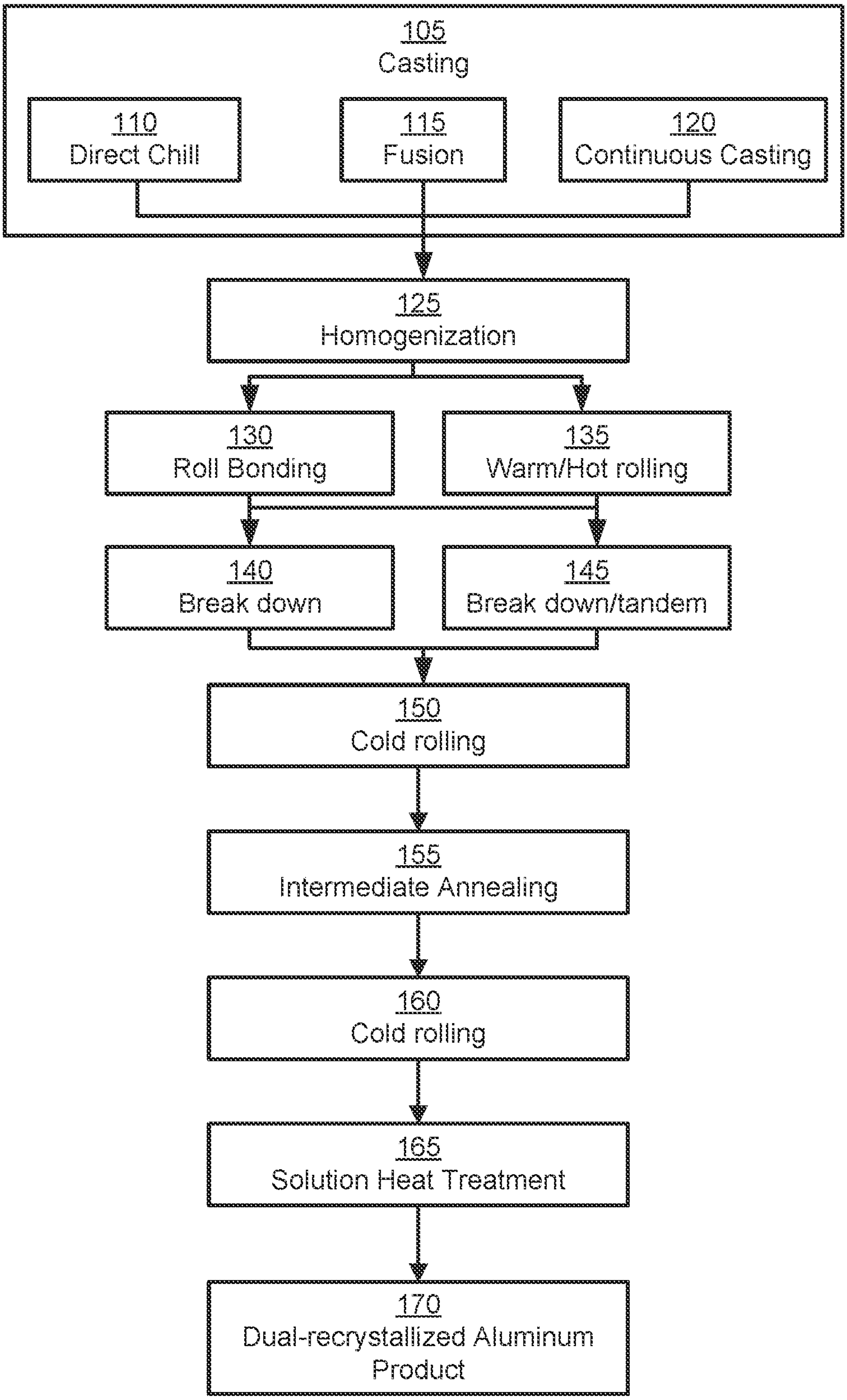

105
Casting
110
Direct Chill
115
Fusion
120
Continuous Casting
125
Homogenization
130
Roll Bonding
135
Warm/Hot rolling
140
Break down
145
Break down/tandem
150
Cold rolling
155
Intermediate Annealing
160
Cold rolling
165
Solution Heat Treatment
170
Dual-recrystallized Aluminum Product

FIG. 1

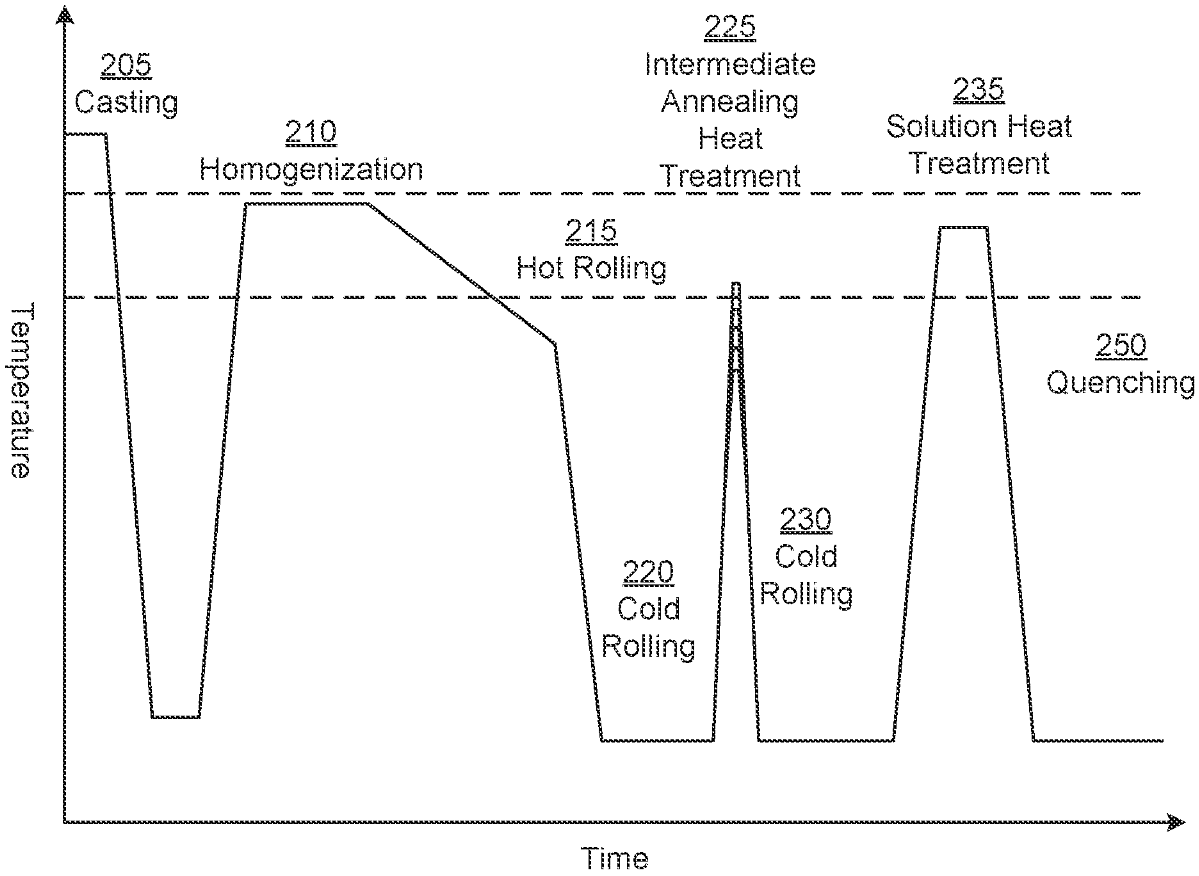

205
Casting
210
Homogenization
225
Intermediate
Annealing
Heat
Treatment
235
Solution Heat
Treatment
215
Hot Rolling
250
Quenching
Temperature
230
Cold
Rolling
220
Cold
Rolling
Time

FIG. 2

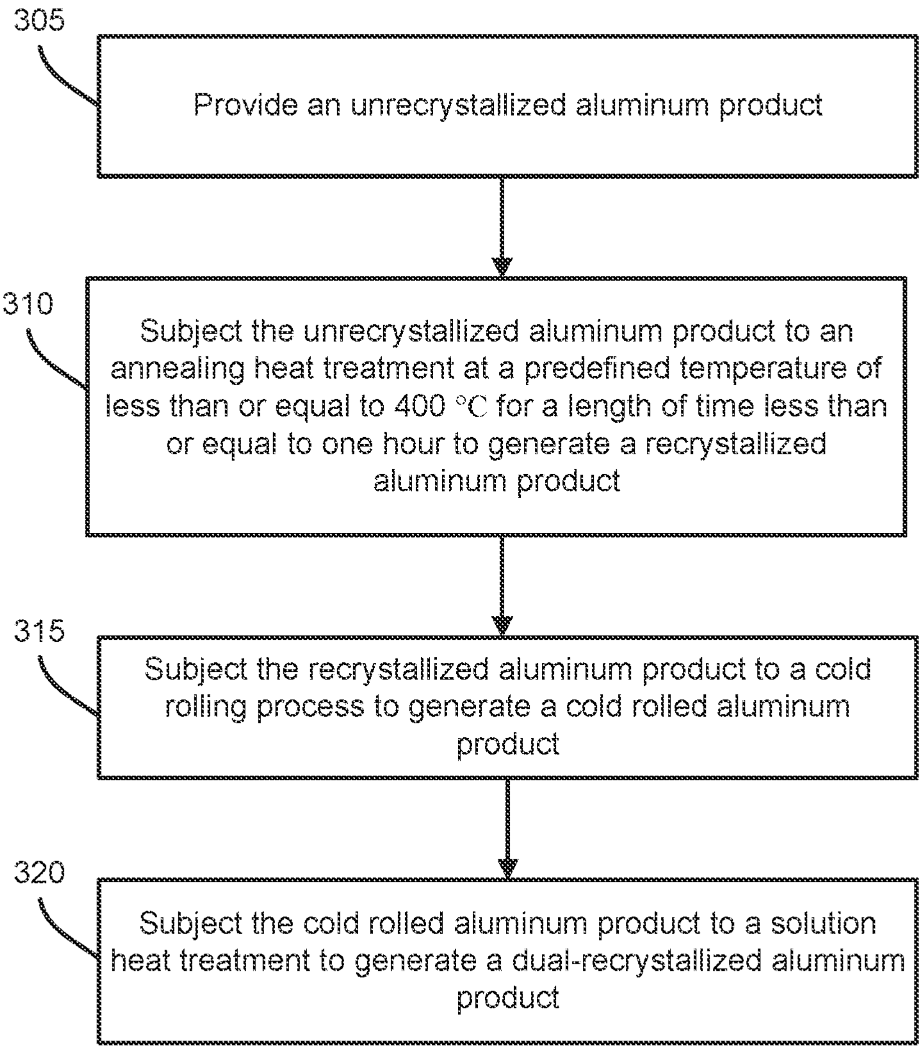

305
Provide an unrecrystallized aluminum product
310
Subject the unrecrystallized aluminum product to an annealing heat treatment at a predefined temperature of less than or equal to 400 °C for a length of time less than or equal to one hour to generate a recrystallized aluminum product
315
Subject the recrystallized aluminum product to a cold rolling process to generate a cold rolled aluminum product
320
Subject the cold rolled aluminum product to a solution heat treatment to generate a dual-recrystallized aluminum product

FIG. 3

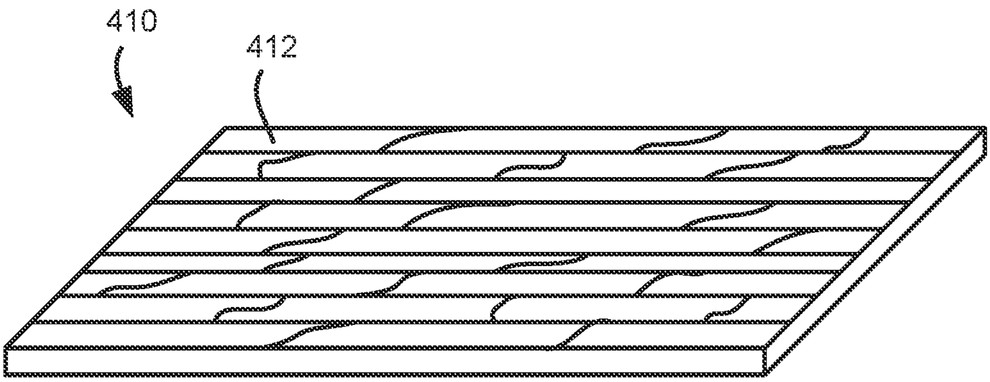


FIG. 4A

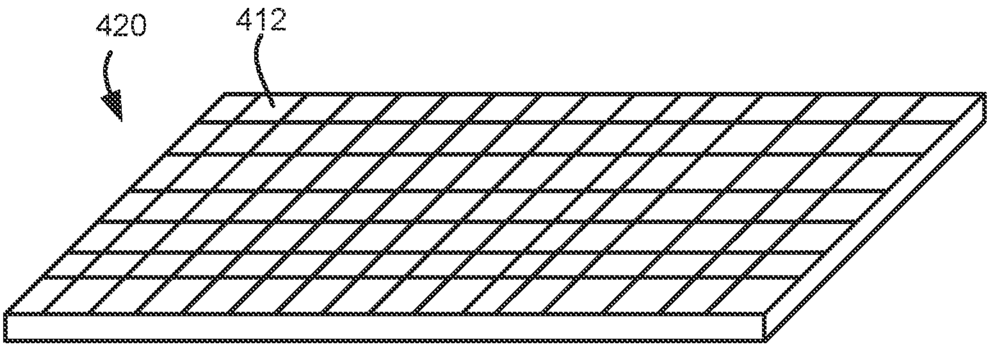
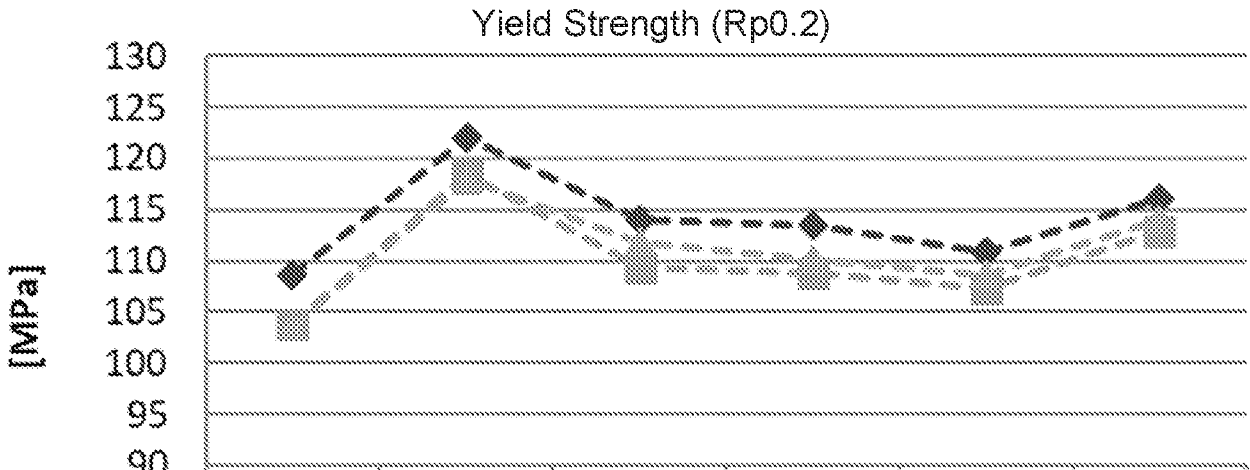
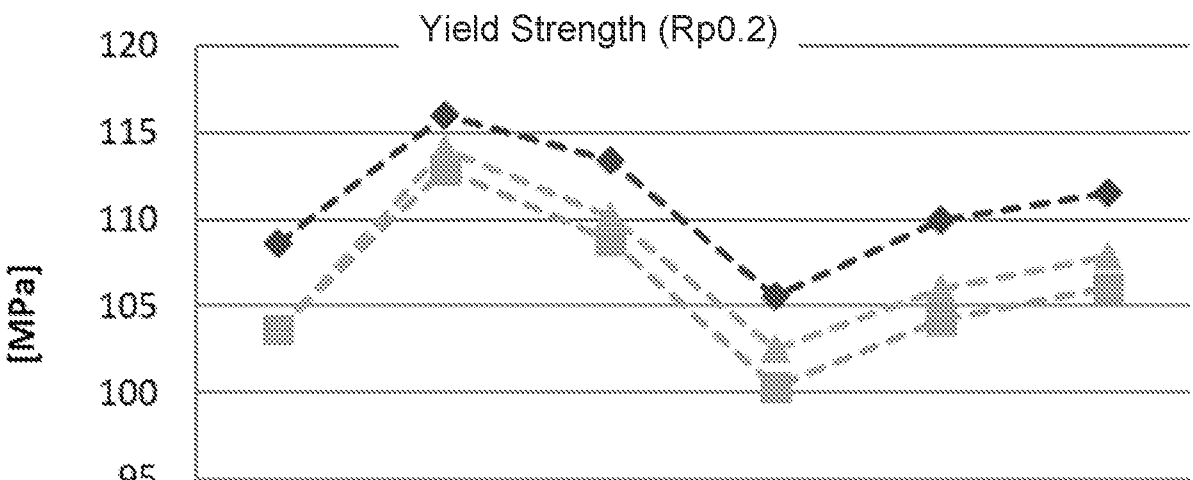


FIG. 4B



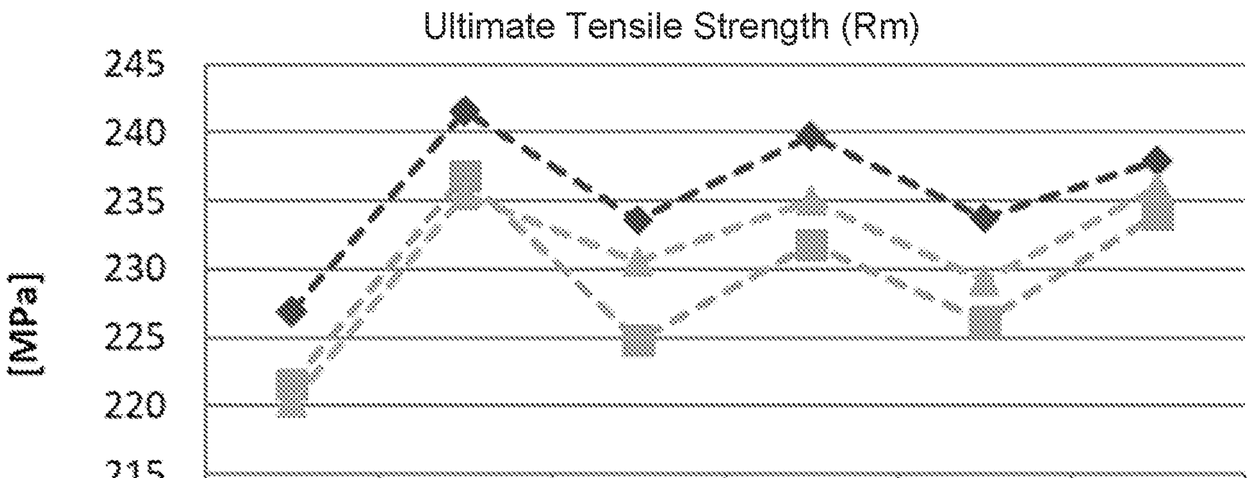
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	109	122	114	113	111	116
T	104	118	109	109	107	113
D	104	118	112	110	109	114

FIG. 5A



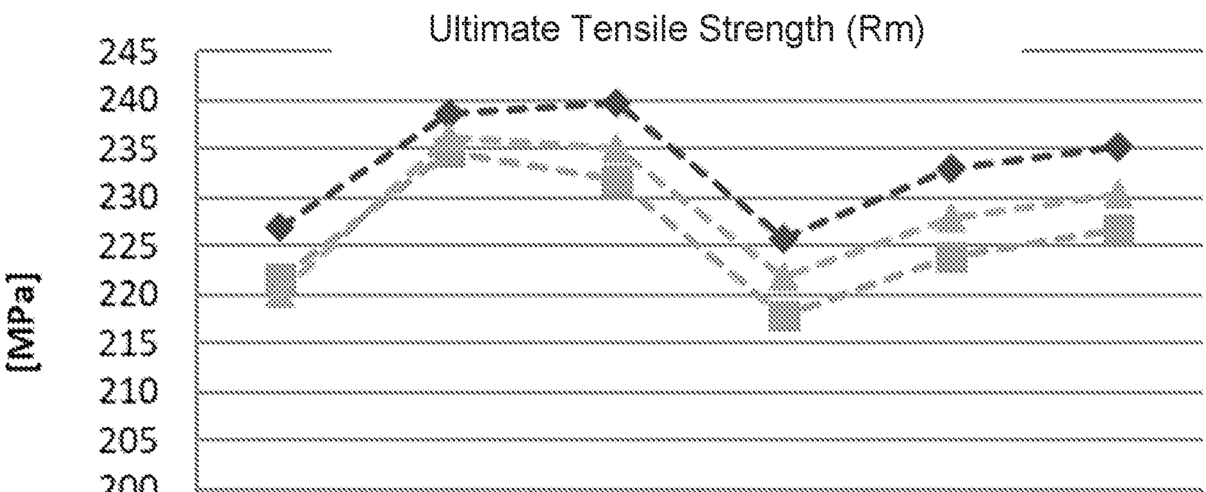
	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	109	116	113	105.56	110	112
T	104	113	109	100.37	104	106
D	104	114	110	102.48	106	108

FIG. 5B



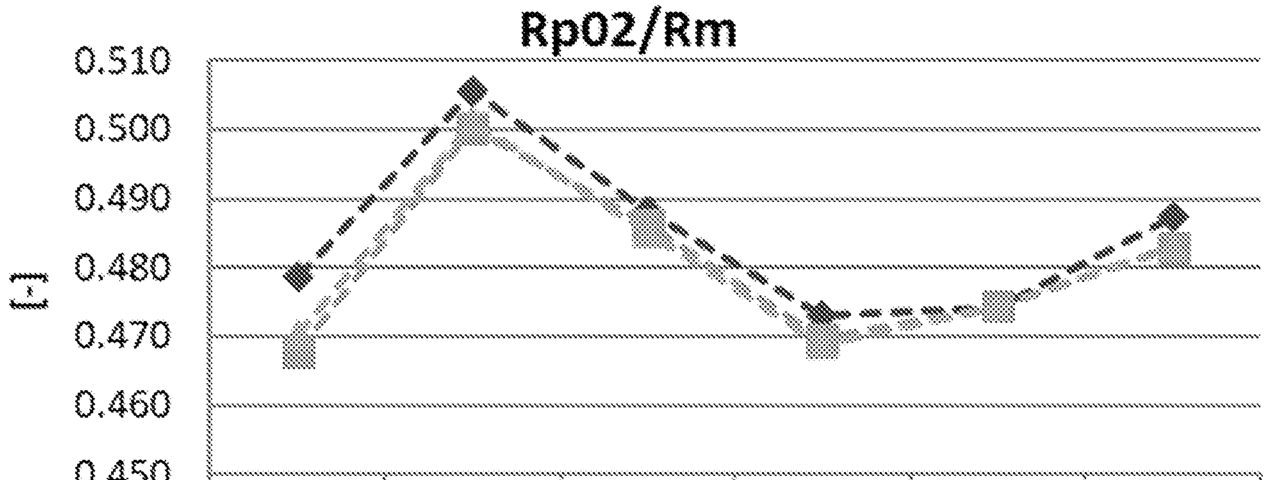
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	227	242	234	240	234	238
T	222	237	225	232	226	234
D	220	235	231	235	229	236

FIG. 5C



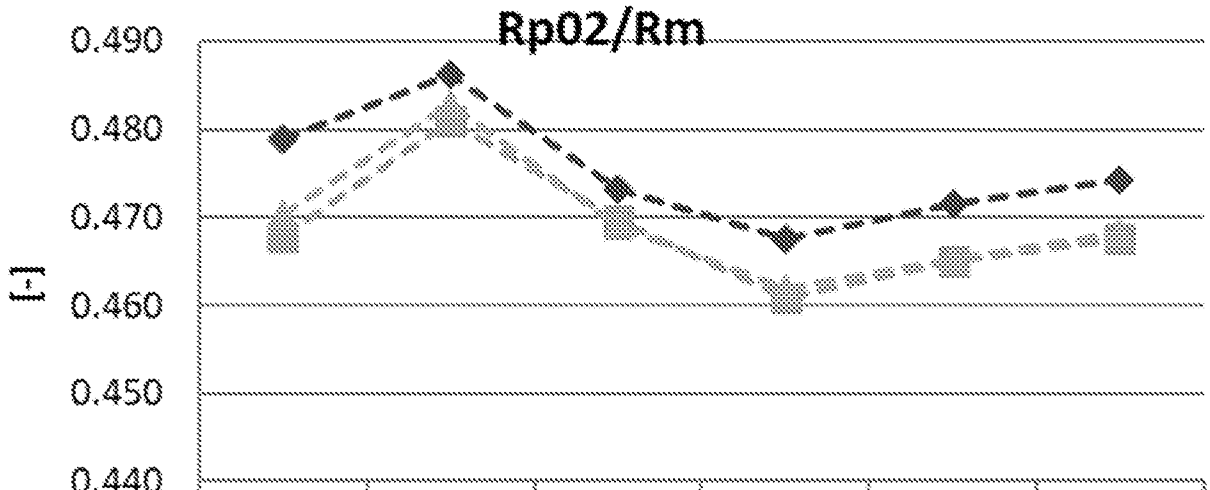
	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	227	239	240	225.8	233	235
T	222	235	232	217.84	224	227
D	220	236	235	221.83	228	230

FIG. 5D



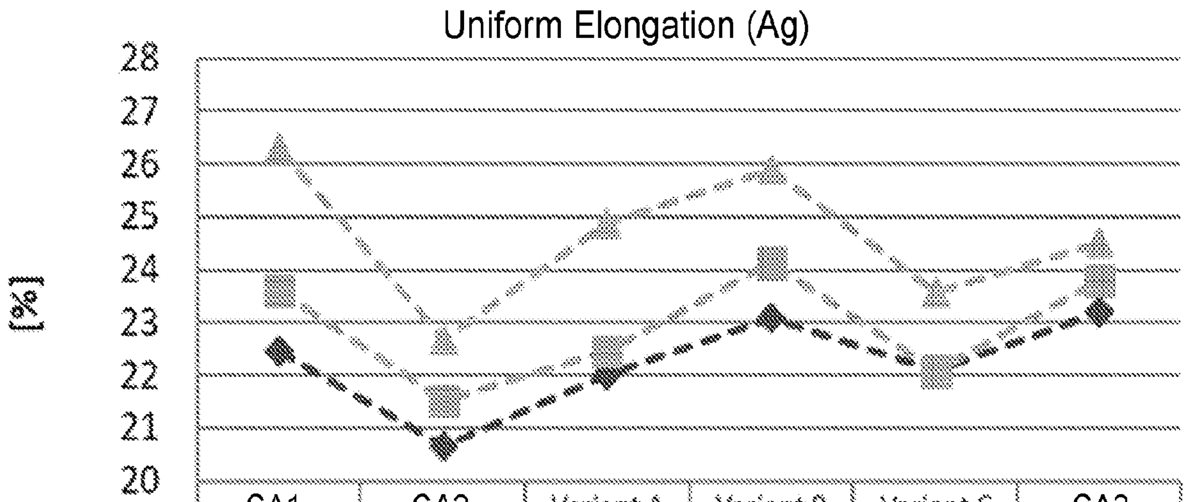
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	0.479	0.506	0.488	0.473	0.474	0.487
T	0.468	0.500	0.486	0.470	0.475	0.483
D	0.470	0.501	0.485	0.469	0.474	0.483

FIG. 5E



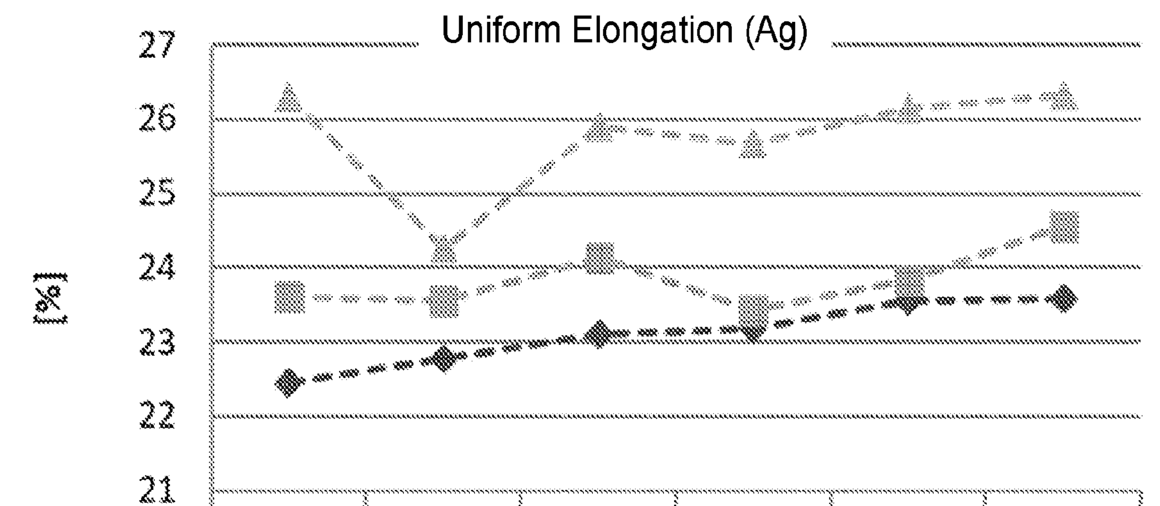
	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	0.479	0.486	0.473	0.467	0.472	0.474
T	0.468	0.481	0.470	0.461	0.465	0.467
D	0.470	0.483	0.469	0.462	0.465	0.468

FIG. 5F



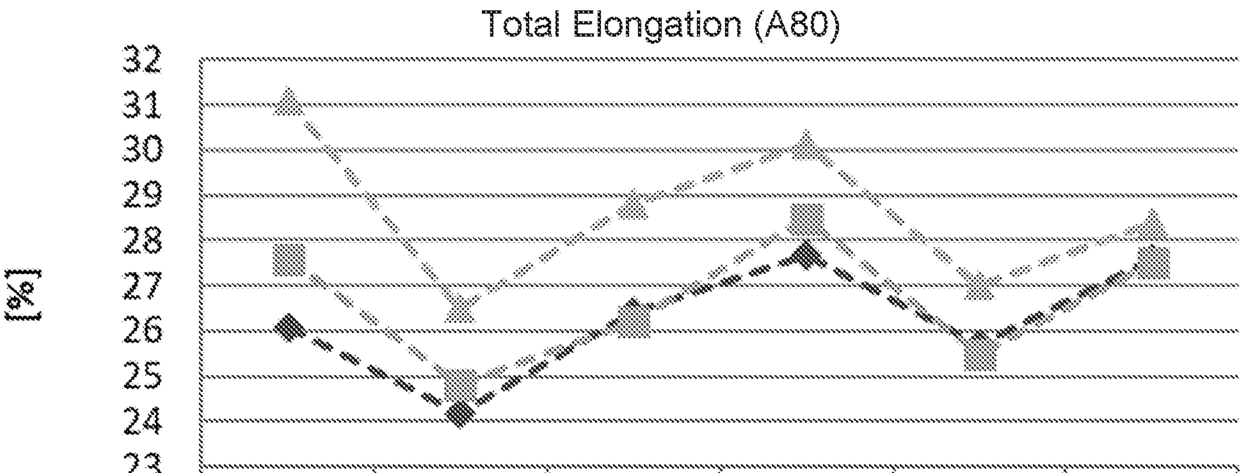
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	22.4	20.7	22.0	23.1	22.1	23.2
T	23.6	21.5	22.5	24.1	22.1	23.8
D	26.3	22.7	24.9	25.9	23.6	24.5

FIG. 6A



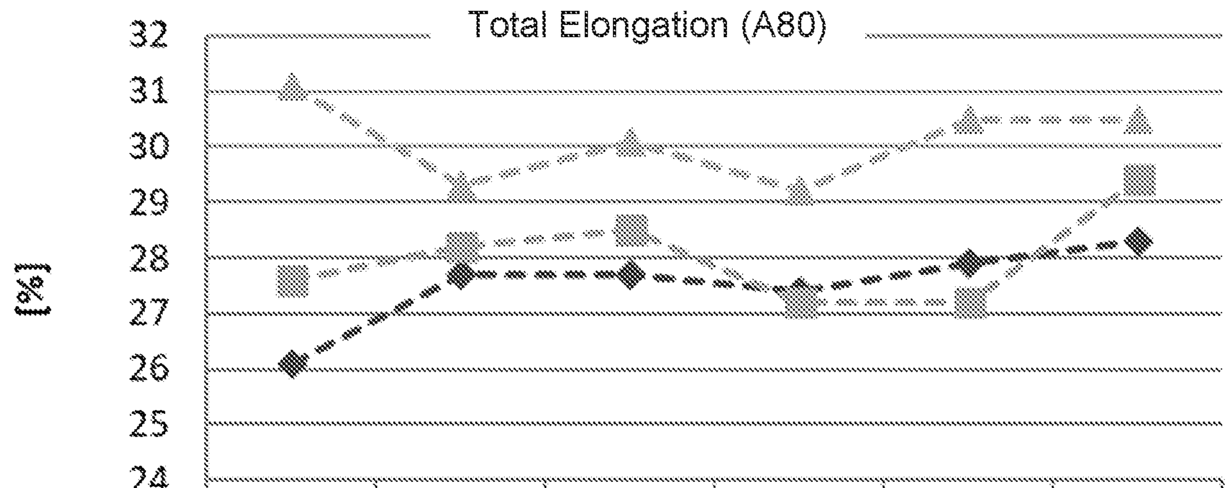
	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	22.4	22.8	23.1	23.2	23.6	23.6
T	23.6	23.6	24.1	23.4	23.8	24.6
D	26.3	24.3	25.9	25.7	26.2	26.3

FIG. 6B



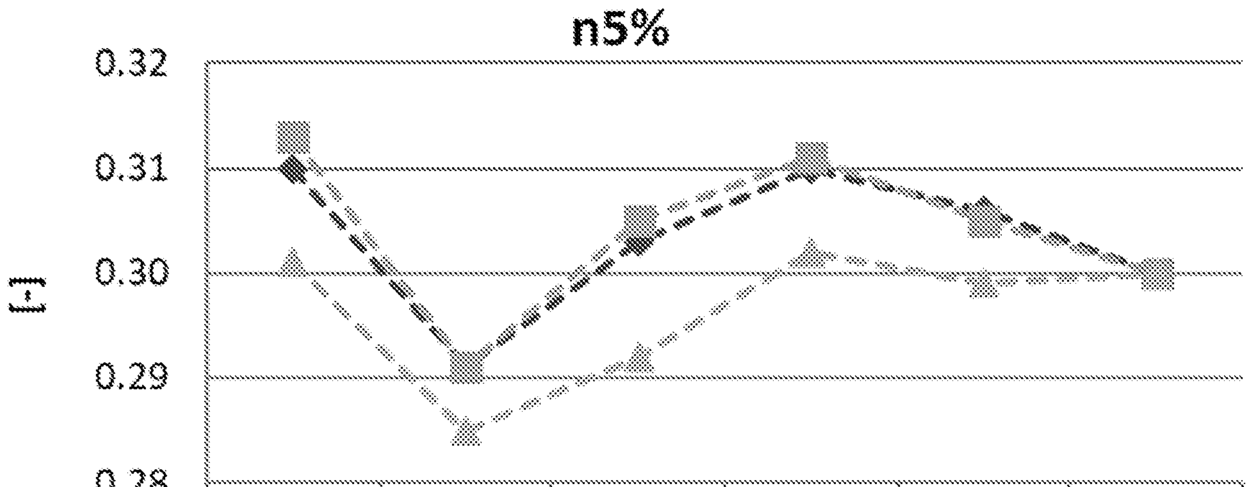
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	26.1	24.2	26.4	27.7	25.7	27.6
T	27.6	24.8	26.2	28.5	25.5	27.5
D	31.1	26.5	28.8	30.1	27.0	28.4

FIG. 6C



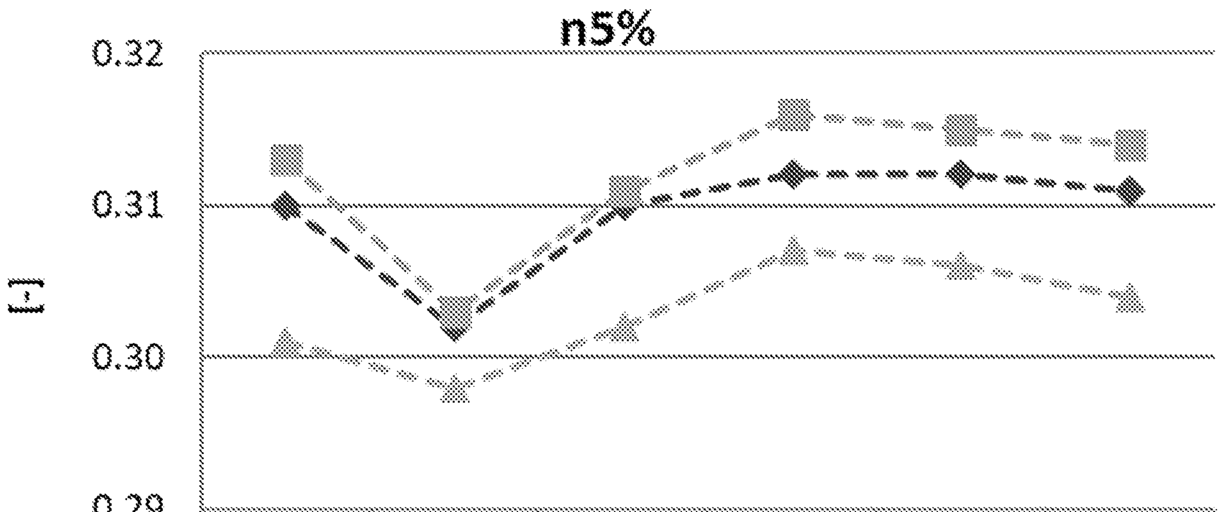
	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	26.1	27.7	27.7	27.4	27.9	28.3
T	27.6	28.2	28.5	27.2	27.2	29.4
D	31.1	29.3	30.1	29.2	30.5	30.5

FIG. 6D



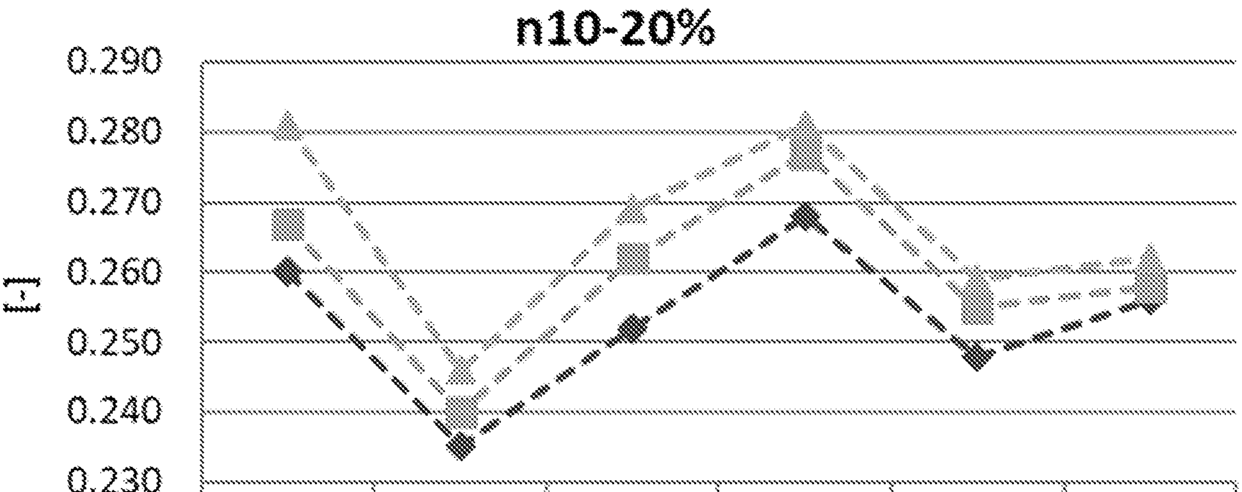
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	0.31	0.29	0.30	0.31	0.31	0.30
T	0.31	0.29	0.31	0.31	0.31	0.30
D	0.30	0.29	0.29	0.30	0.30	0.30

FIG. 6E



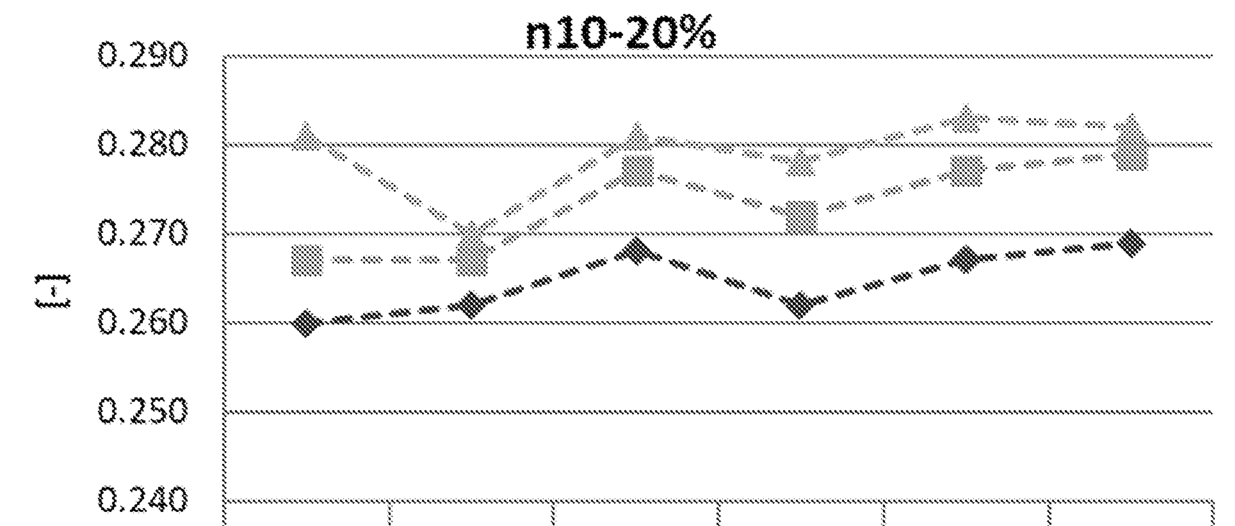
	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	0.31	0.30	0.31	0.31	0.31	0.31
T	0.31	0.30	0.31	0.32	0.32	0.31
D	0.30	0.30	0.30	0.31	0.31	0.30

FIG. 6F



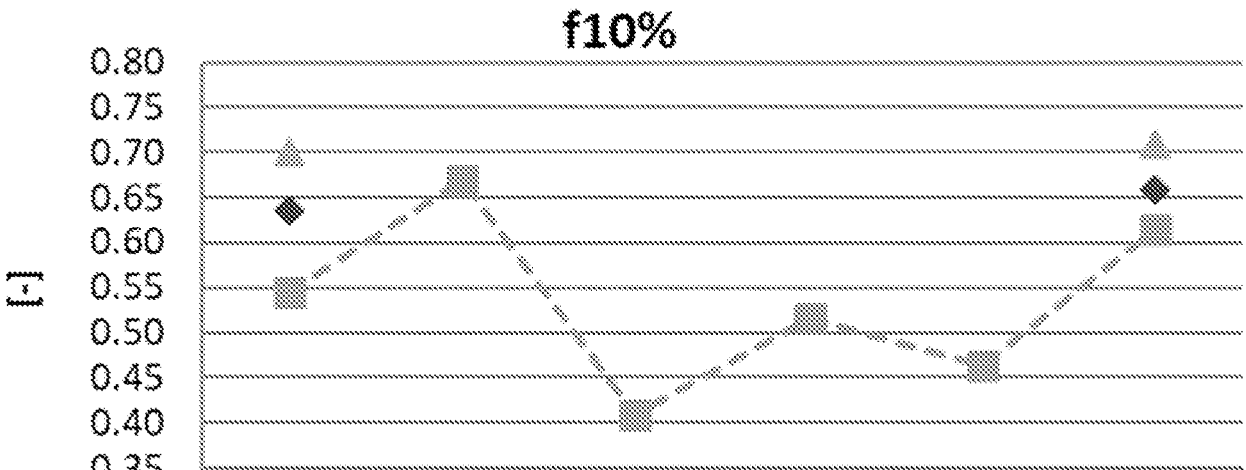
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	0.260	0.235	0.252	0.268	0.248	0.256
T	0.267	0.240	0.262	0.277	0.255	0.258
D	0.281	0.246	0.269	0.281	0.259	0.262

FIG. 6G



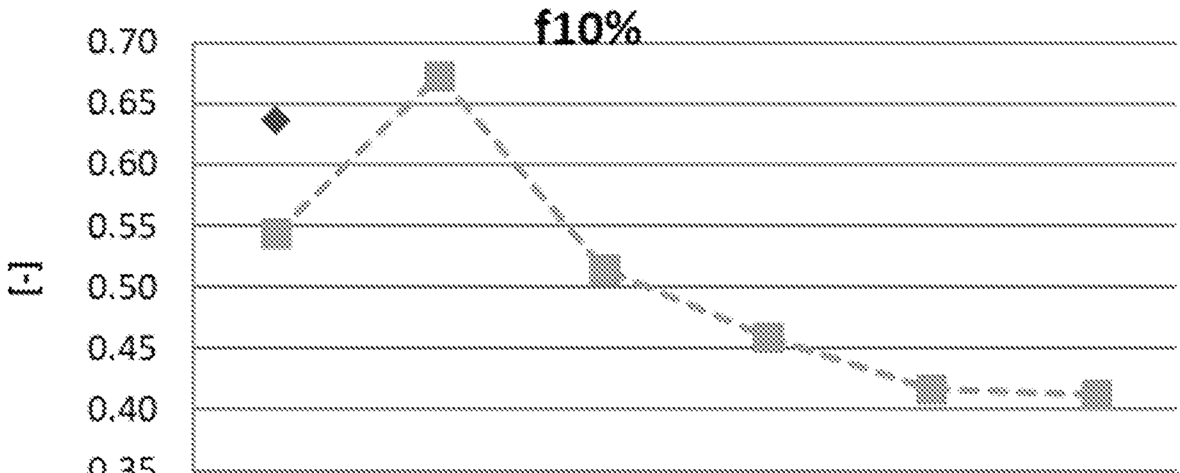
	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	0.260	0.262	0.268	0.262	0.267	0.269
T	0.267	0.267	0.277	0.272	0.277	0.279
D	0.281	0.270	0.281	0.278	0.283	0.282

FIG. 6H



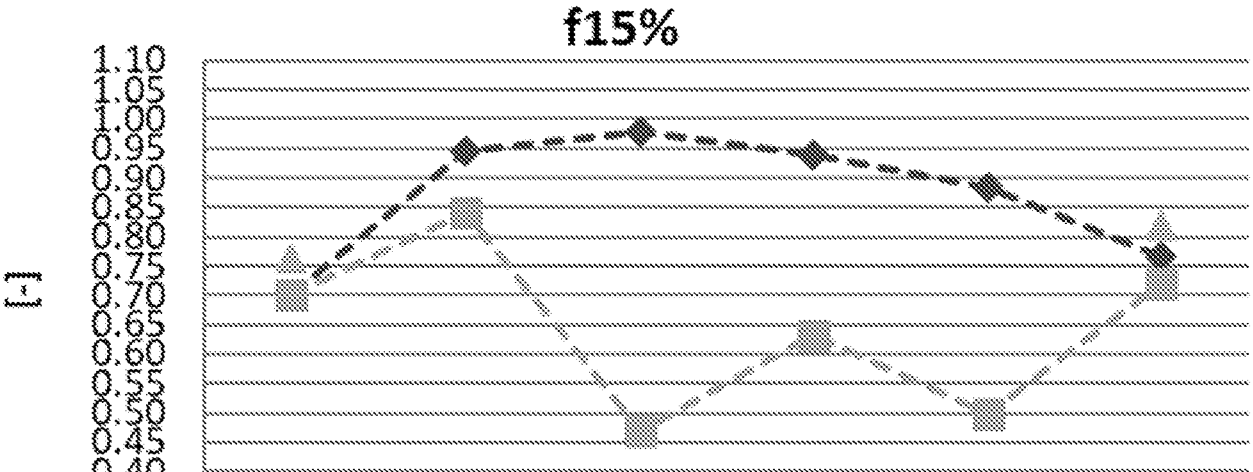
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	0.64					0.66
T	0.55	0.67	0.41	0.52	0.46	0.61
D	0.70					0.71

FIG. 7A



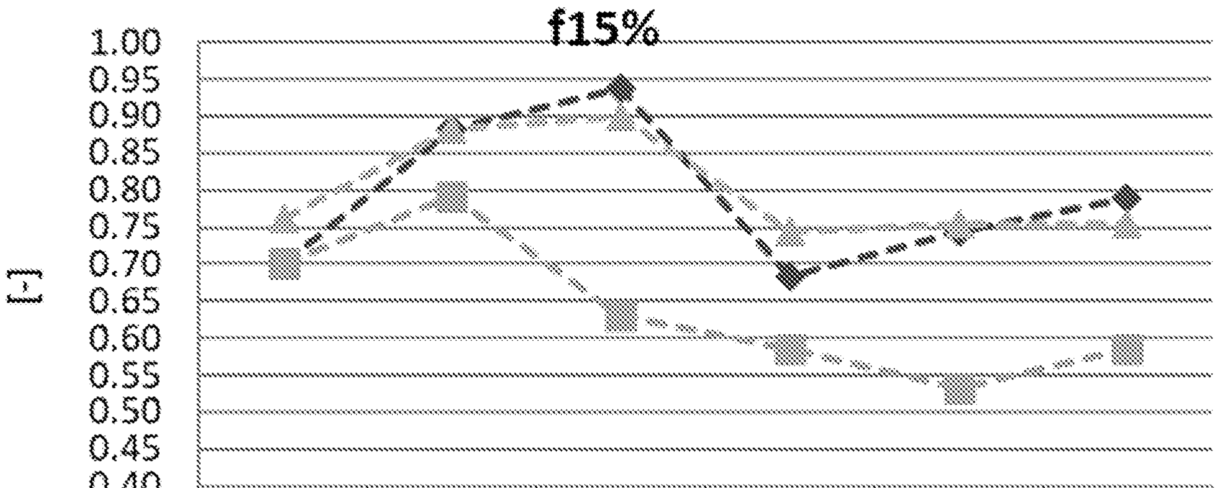
	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	0.64					
T	0.55	0.67	0.52	0.46	0.42	0.41
D	0.70					

FIG. 7B



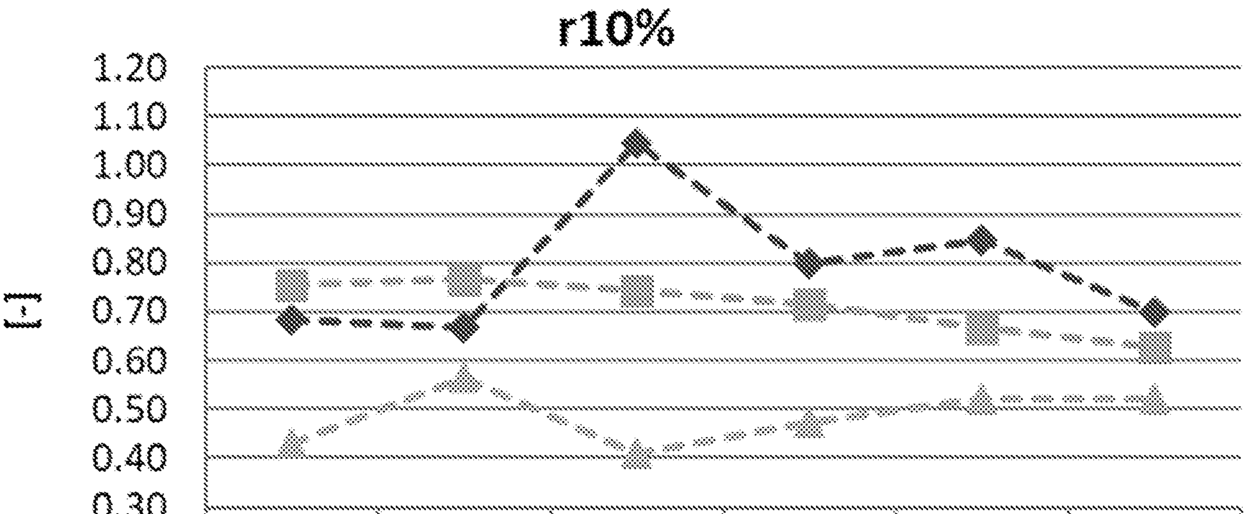
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	0.70	0.95	0.98	0.94	0.89	0.77
T	0.70	0.84	0.47	0.63	0.50	0.72
D	0.76					0.82

FIG. 7C



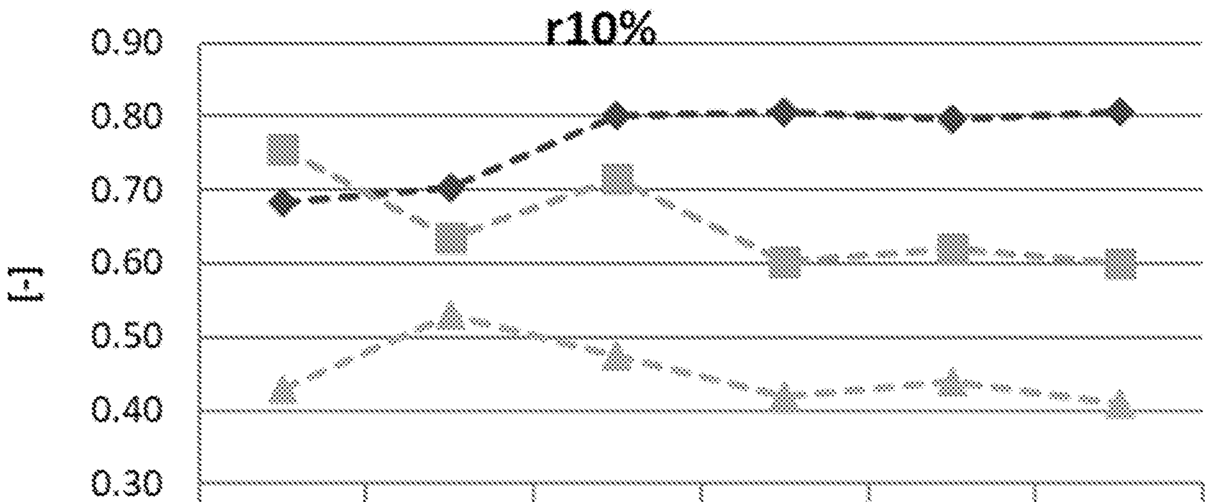
	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	0.70	0.88	0.94	0.68	0.75	0.79
T	0.70	0.79	0.63	0.59	0.53	0.59
D	0.76	0.88	0.90	0.75	0.75	0.75

FIG. 7D



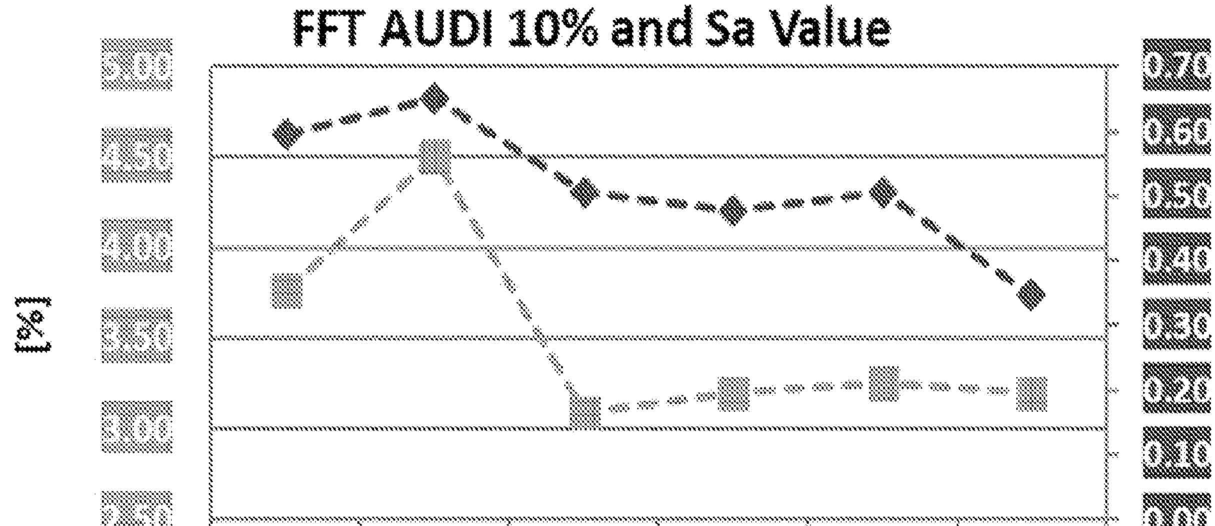
	CA1	CA2	Variant A	Variant B	Variant C	CA3
L	0.68	0.67	1.05	0.80	0.85	0.70
T	0.76	0.77	0.74	0.72	0.67	0.63
D	0.43	0.57	0.41	0.48	0.52	0.52

FIG. 7E



	CA1	CA4	Variant B	Variant D	Variant E	Variant F
L	0.68	0.70	0.80	0.81	0.80	0.81
T	0.76	0.64	0.72	0.60	0.62	0.60
D	0.43	0.53	0.48	0.42	0.44	0.41

FIG. 7F



	CA1	CA2	Variant A	Variant B	Variant C	CA3
FFT T	3.77	4.50	3.09	3.20	3.26	3.20
Sa T	0.60	0.65	0.51	0.48	0.51	0.35

FIG. 7G

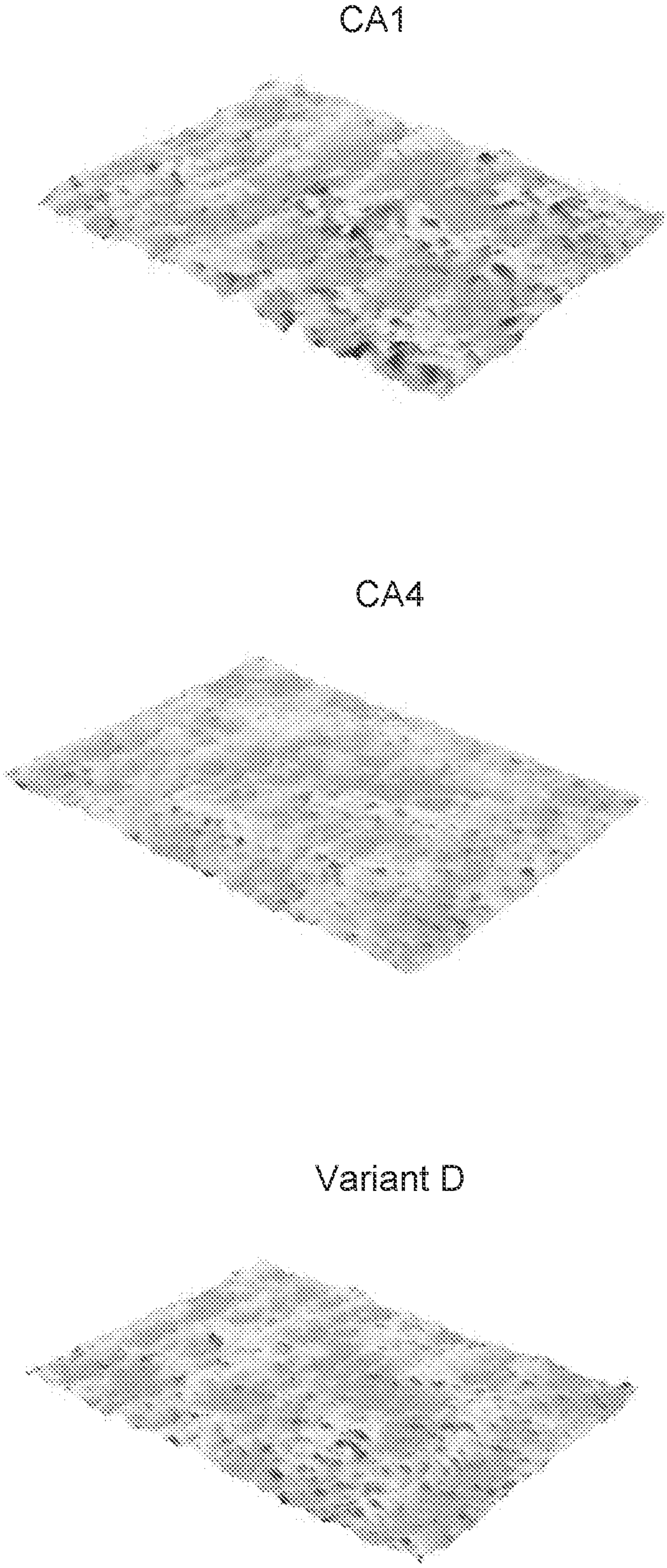


FIG. 8

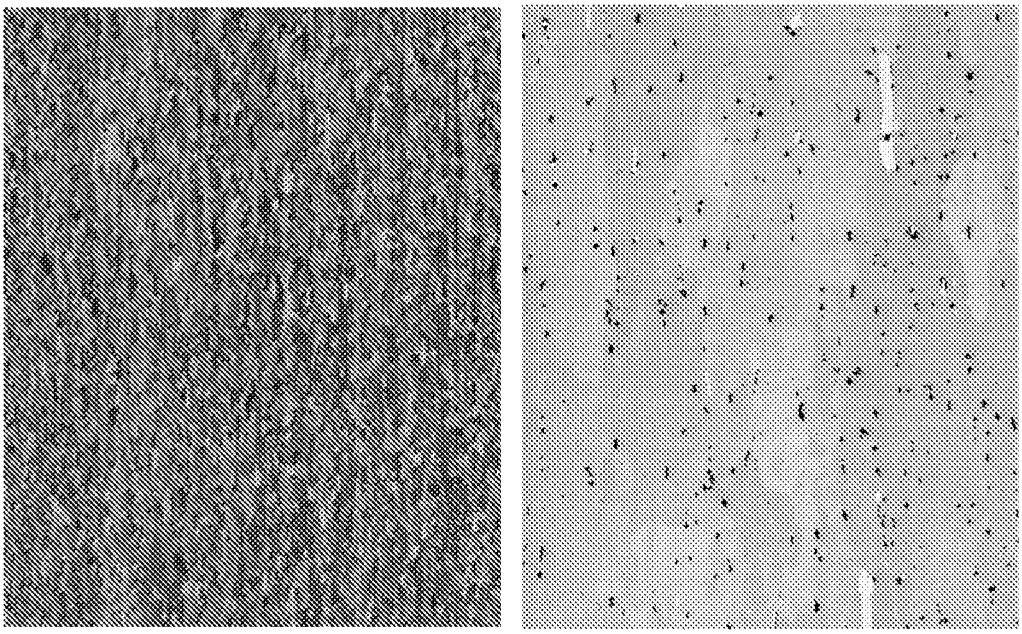


FIG. 9C

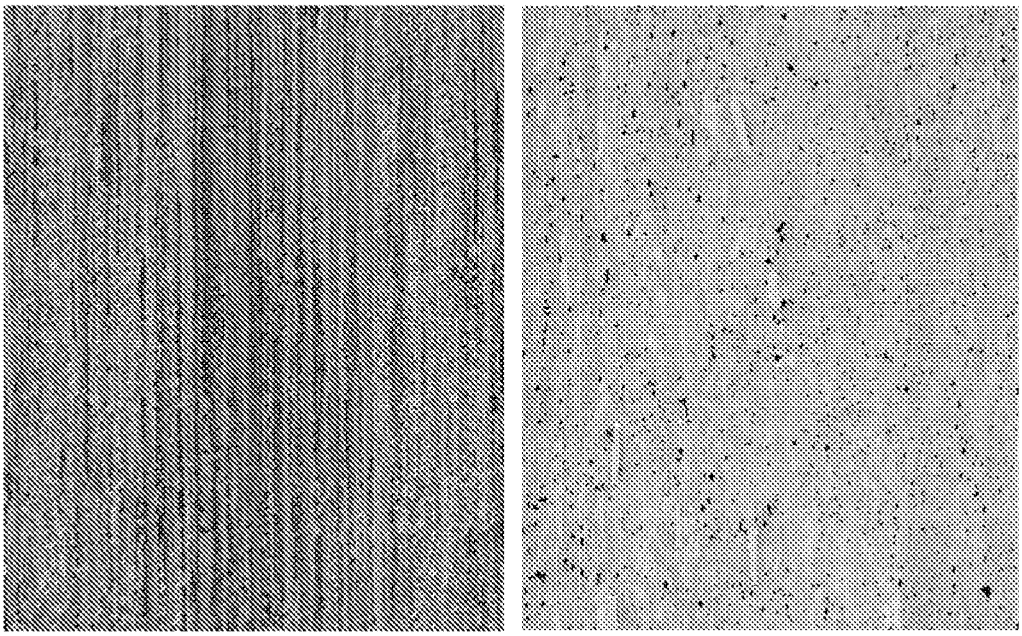


FIG. 9B

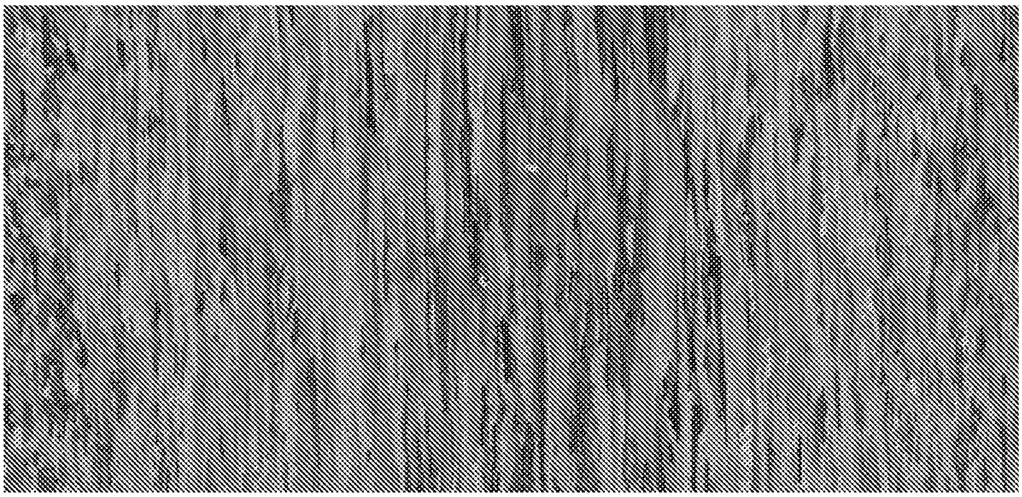


FIG. 9A

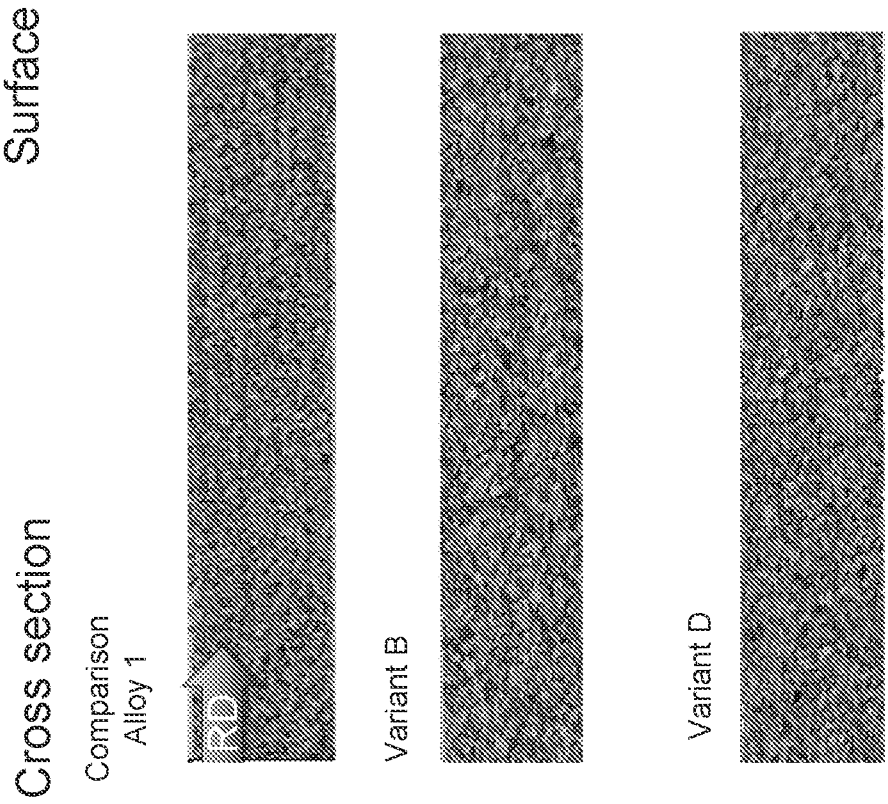


FIG. 10A

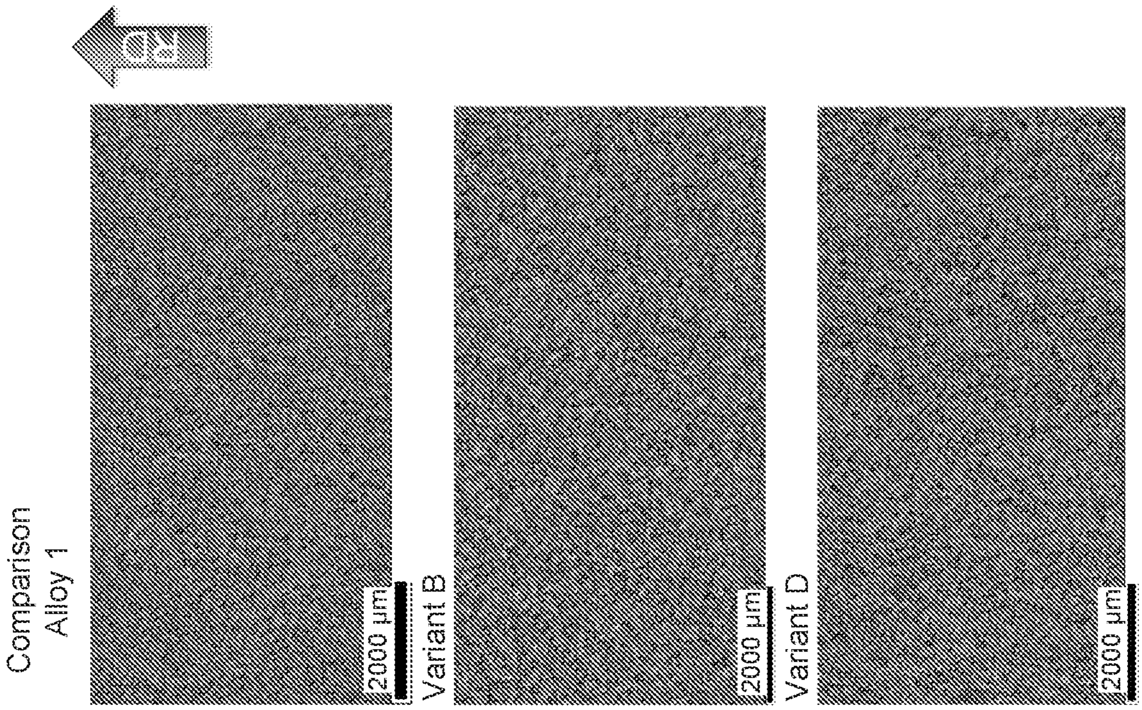


FIG. 10B

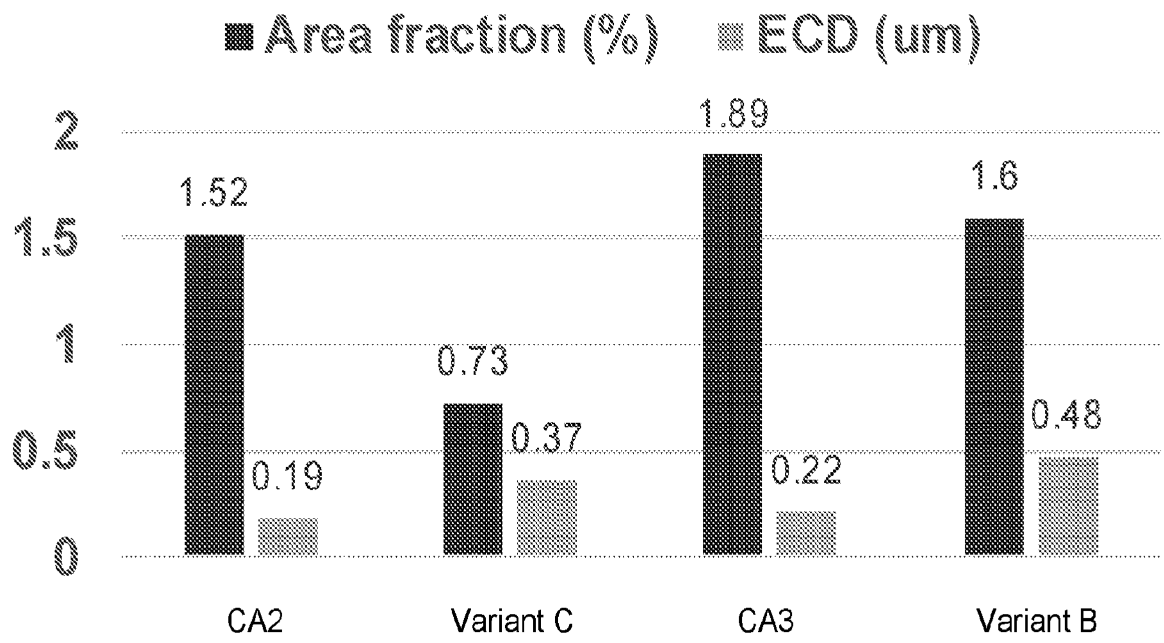


FIG. 11A

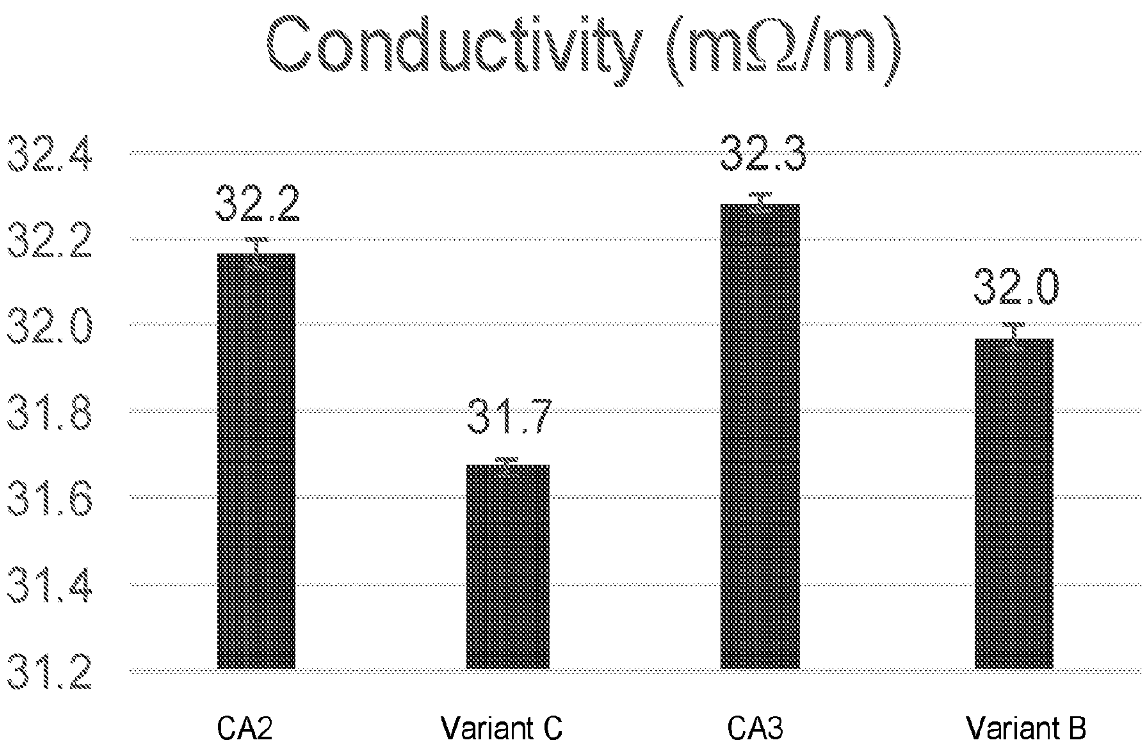


FIG. 11B

20/22

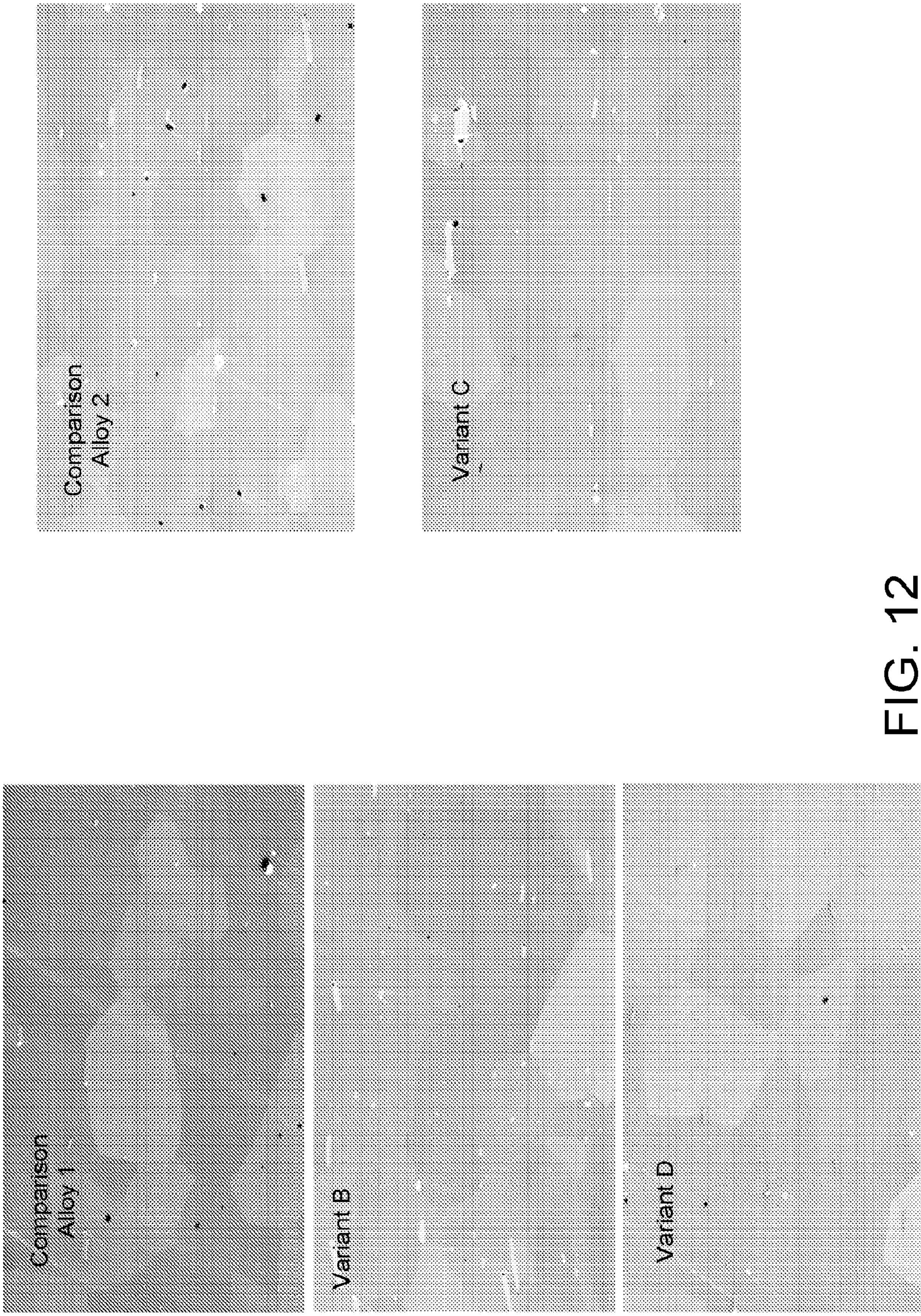

Comparison Alloy 2
Variant C
Comparison Alloy 1
Variant B
Variant D

FIG. 12

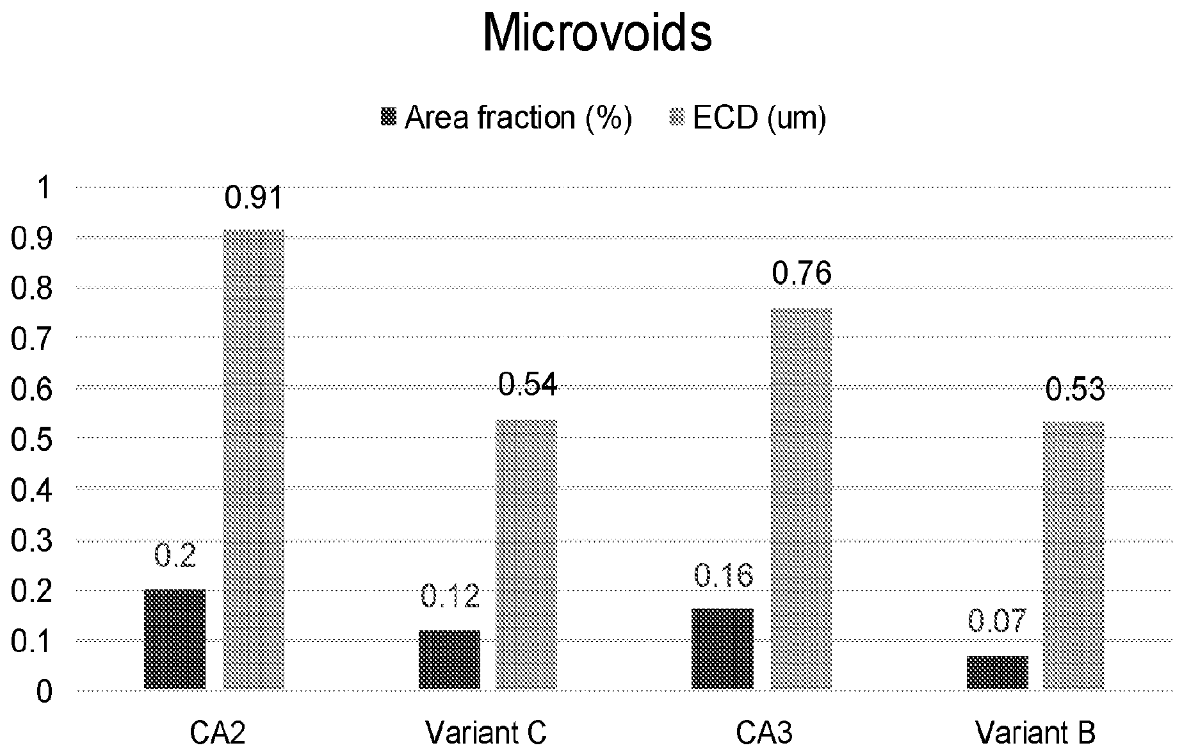


FIG. 13A

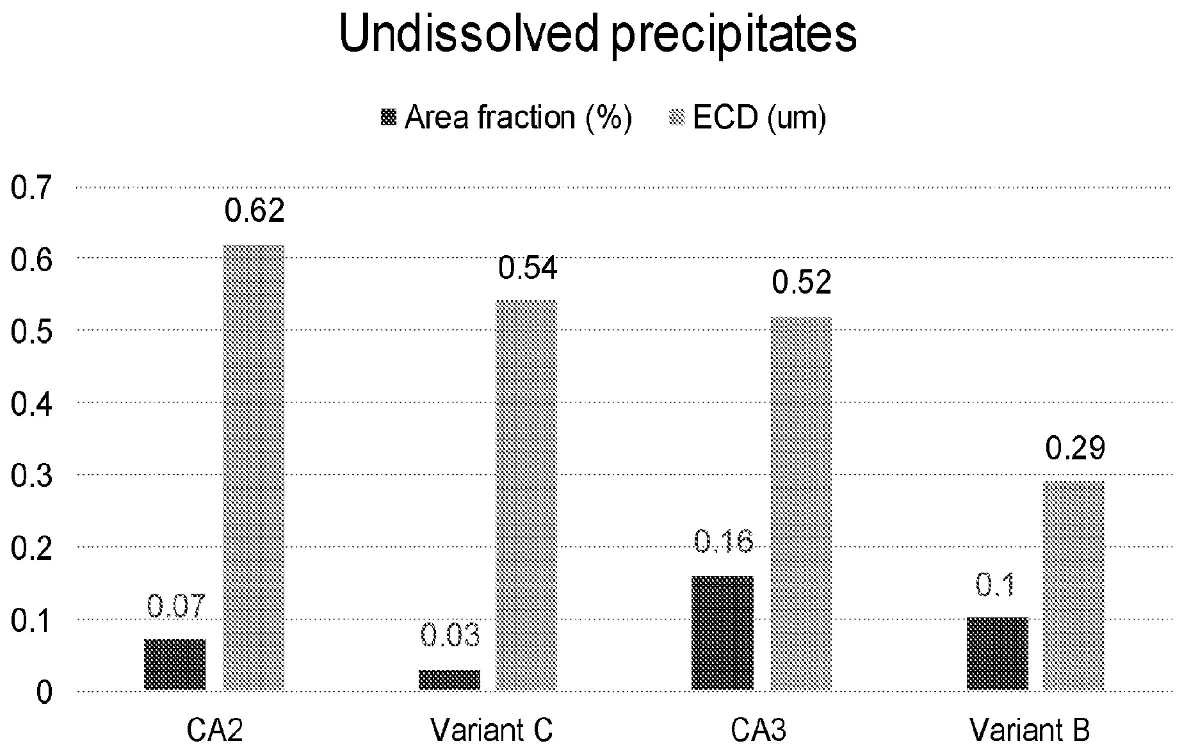


FIG. 13B

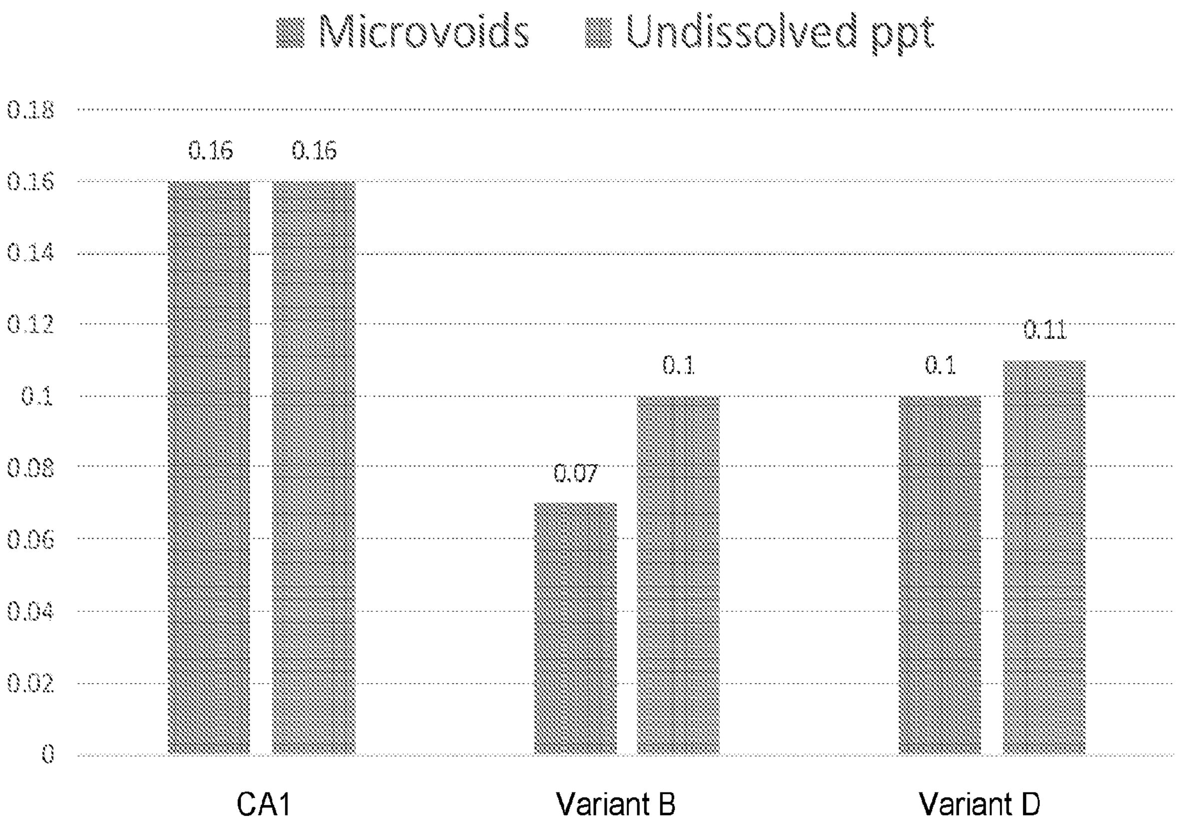

Microvoids
Undissolved ppt
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.16
0.16
0.07
0.1
0.1
0.11
CA1
Variant B
Variant D

FIG. 14

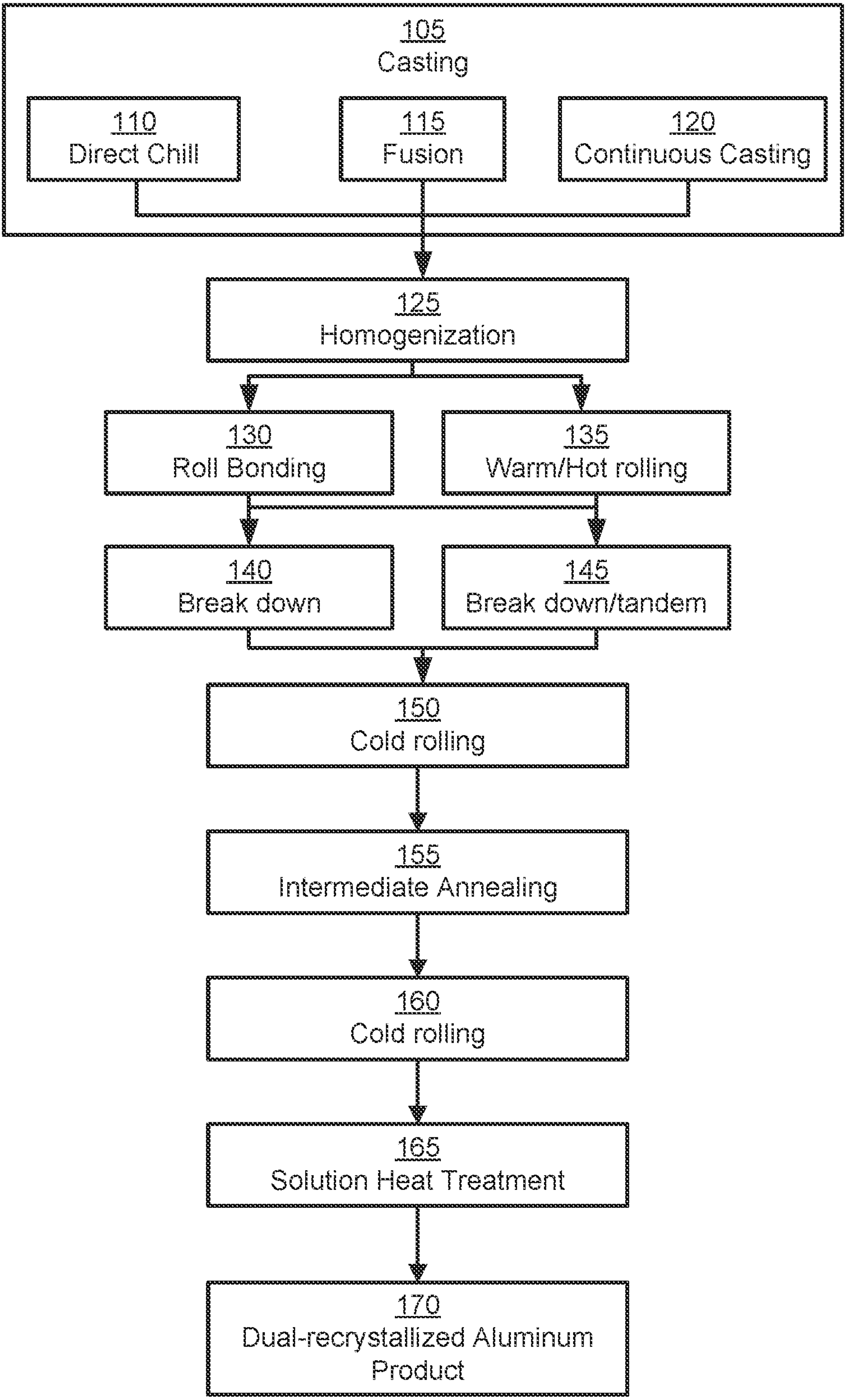

105
Casting
110
Direct Chill
115
Fusion
120
Continuous Casting
125
Homogenization
130
Roll Bonding
135
Warm/Hot rolling
140
Break down
145
Break down/tandem
150
Cold rolling
155
Intermediate Annealing
160
Cold rolling
165
Solution Heat Treatment
170
Dual-recrystallized Aluminum Product

FIG. 1