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(71) Applicant: **ARCONIC INC.** [US/US]; 201 Isabella Street,
Pittsburgh, Pennsylvania 15212-5858 (US).

(72) Inventors: **HOSCH, Timothy A.**; 165 Chavelle Court,
Plum, Pennsylvania 15239 (US). **MOOY, Dirk C.**; 5148
Black Hawk Trail Court, Bettendorf, Iowa 52722 (US).
BELL, Cyril F.; 1617 Mimosa Drive, Louisville, Ten-
nessee 37777 (US).

(74) Agent: **BRIGGS, Heath J.** et al.; ARCONIC INC., c/
o Greenberg Traurig, LLP, 500 Campus Drive, Suite 400,
Florham Park, New Jersey 07932 (US).

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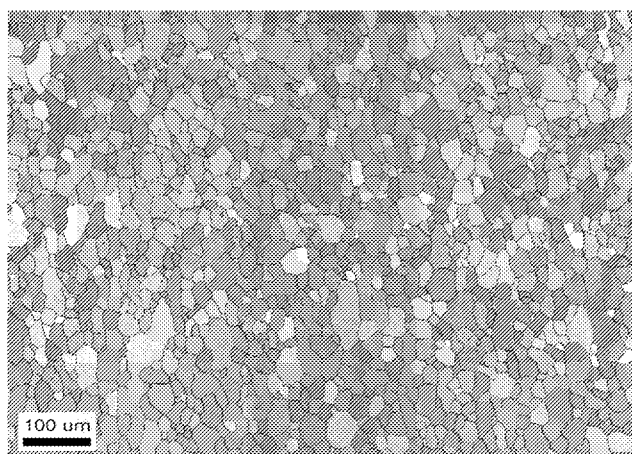


FIG. 1: Alloy A1-1.

(57) Abstract: New 6xxx aluminum alloys having an improved combination of properties are disclosed. The new 6xxx aluminum alloy generally include 0.65 - 0.85 wt. % Si, 0.40 - 0.59 wt. % Mg, wherein (wt. % Mg) / (wt. % Si) is from 0.47 to 0.90, 0.05 - 0.35 wt. % Fe, 0.04 - 0.13 wt. % Mn, 0 - 0.20 wt. % Cu, 0 - 0.15 wt. % Cr, 0 - 0.15 wt. % Zr, 0 - 0.15 wt. % Ti, 0 - 0.10 wt. % Zn, 0 - 0.05 wt. % V, the balance being aluminum and impurities.



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6XXX ALUMINUM ALLOYS

BACKGROUND

[001] Aluminum alloys are useful in a variety of applications. However, improving one property of an aluminum alloy without degrading another property often proves elusive. For example, it is difficult to increase the strength of an alloy without decreasing its corrosion resistance. Other properties of interest for aluminum alloys include formability and critical fracture strain, to name two.

SUMMARY OF THE DISCLOSURE

[002] Broadly, the present disclosure relates to new 6xxx aluminum alloys having an improved combination of properties, such as an improved combination of strength, formability, bending, and/or corrosion resistance, among others.

i. Composition

[003] Generally, the new 6xxx aluminum alloys comprise (and in some instances consist essentially of or consist of) from 0.65 to 0.85 wt. % Si, from 0.40 to 0.59 wt. % Mg wherein the ratio of wt. % Mg to wt. % Si is from 0.47:1 to 0.90:1 (Mg:Si), from 0.05 to 0.35 wt. % Fe, from 0.04 to 0.13 wt. % Mn, from 0 to 0.20 wt. % Cu, from 0 to 0.15 wt. % Cr, from 0 to 0.15 wt. % Zr, from 0 to 0.10 wt. % Ti, from 0 to 0.05 wt. % V, from 0 to 0.05 wt. % Zn, the balance being aluminum and impurities.

[004] The amount of magnesium (Mg) and silicon (Si) in the new 6xxx aluminum alloys may relate to the improved combination of properties (e.g., strength, formability). Generally, the new 6xxx aluminum alloy includes from 0.40 to 0.59 wt. % Mg. In one embodiment, a new 6xxx aluminum alloy includes at least 0.425 wt. % Mg. In another embodiment, a new 6xxx aluminum alloy includes at least 0.45 wt. % Mg. In yet another embodiment, a new 6xxx aluminum alloy includes at least 0.475 wt. % Mg. In another embodiment, a new 6xxx aluminum alloy includes at least 0.50 wt. % Mg. In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.57 wt. % Mg. In one embodiment, a new 6xxx aluminum alloy includes from 0.49 to 0.59 wt. % Mg.

[005] Generally, the new 6xxx aluminum alloy includes from 0.65 to 0.85 wt. % Si. In one embodiment, a new 6xxx aluminum alloy includes at least 0.675 wt. % Si. In another embodiment, a new 6xxx aluminum alloy includes at least 0.70 wt. % Si. In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.825 wt. % Si. In another embodiment,

a new 6xxx aluminum alloy includes not greater than 0.80 wt. % Si. In one embodiment, a new 6xxx aluminum alloy includes from 0.70 to 0.80 wt. % Si.

[006] Generally, the new 6xxx aluminum alloy includes silicon and magnesium such that the weight ratio of magnesium-to-silicon of from 0.47:1 to 0.90:1, i.e., the ratio of wt. % Mg to wt. % Si is from 0.47:1 to 0.90:1 (Mg:Si). In one embodiment, the ratio of wt. % Mg to wt. % Si is at least 0.50:1(Mg:Si). In another embodiment, the ratio of wt. % Mg to wt. % Si is at least 0.52:1(Mg:Si). In yet another embodiment, the ratio of wt. % Mg to wt. % Si is at least 0.54:1(Mg:Si). In another embodiment, the ratio of wt. % Mg to wt. % Si is at least 0.56:1(Mg:Si). In yet another embodiment, the ratio of wt. % Mg to wt. % Si is at least 0.58:1(Mg:Si). In another embodiment, the ratio of wt. % Mg to wt. % Si is at least 0.60:1(Mg:Si). In one embodiment, the ratio of wt. % Mg to wt. % Si is not greater than 0.88:1(Mg:Si). In another embodiment, the ratio of wt. % Mg to wt. % Si is not greater than 0.86:1(Mg:Si). In yet another embodiment, the ratio of wt. % Mg to wt. % Si is not greater than 0.84:1(Mg:Si). In another embodiment, the ratio of wt. % Mg to wt. % Si is not greater than 0.82:1(Mg:Si). In one embodiment, the ratio of wt. % Mg to wt. % Si is from 0.61:1 to 0.84:1 (Mg:Si).

[007] Iron (Fe) is generally included in the new 6xxx aluminum alloy, and in the range of from 0.05 to 0.35 wt. % Fe. In one embodiment, a new 6xxx aluminum alloy includes at least 0.08 wt. % Fe. In another one embodiment, a new 6xxx aluminum alloy includes at least 0.10 wt. % Fe. In yet another embodiment, a new 6xxx aluminum alloy includes at least 0.12 wt. % Fe. In another embodiment, a new 6xxx aluminum alloy includes at least 0.15 wt. %. In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.32 wt. % Fe. In another embodiment, a new 6xxx aluminum alloy includes not greater than 0.30 wt. % Fe. In yet another embodiment, a new 6xxx aluminum alloy includes not greater than 0.28 wt. % Fe. In one embodiment, a new 6xxx aluminum alloy includes from 0.09 to 0.26 wt. % Fe.

[008] The amount of manganese (Mn) in the new 6xxx aluminum alloys may relate to the improved combination of properties (e.g., formability). Generally, the new 6xxx aluminum alloy includes from 0.04 to 0.13 wt. % Mn. In one embodiment, a new 6xxx aluminum alloy includes at least 0.05 wt. % Mn. In another embodiment, a new 6xxx aluminum alloy includes at least 0.06 wt. % Mn. In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.12 wt. % Mn. In another embodiment, a new 6xxx aluminum alloy includes not greater than 0.11 wt. % Mn. In another embodiment, a new 6xxx aluminum alloy includes not greater than 0.10 wt. % Mn. In one embodiment, a new 6xxx aluminum alloy includes from 0.06 to 0.10 wt. % Mn.

[0009] The new 6xxx aluminum alloy may optionally include copper (Cu) and in an amount of up to 0.20 wt. % Cu (e.g., for strengthening purposes). In one embodiment, a new 6xxx aluminum alloy includes at least 0.02 wt. % Cu. In another embodiment, a new 6xxx aluminum alloy includes at least 0.04 wt. % Cu. In yet another embodiment, a new 6xxx aluminum alloy includes at least 0.06 wt. % Cu. In another embodiment, a new 6xxx aluminum alloy includes at least 0.07 wt. % Cu. In yet another embodiment, a new 6xxx aluminum alloy includes at least 0.08 wt. % Cu. In another embodiment, a new 6xxx aluminum alloy includes at least 0.09 wt. % Cu. In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.19 wt. % Cu. In another embodiment, a new 6xxx aluminum alloy includes not greater than 0.18 wt. % Cu. In yet another embodiment, a new 6xxx aluminum alloy includes not greater than 0.17 wt. % Cu. In one embodiment, a new 6xxx aluminum alloy includes from 0.09 to 0.17 wt. % Cu.

[0010] The new 6xxx aluminum alloy may optionally include chromium (Cr) and in an amount of up to 0.15 wt. % Cr (e.g., for grain structure control). In one embodiment, a new 6xxx aluminum alloy includes at least 0.01 wt. % Cr. In another embodiment, a new 6xxx aluminum alloy includes at least 0.02 wt. % Cr. In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.10 wt. % Cr. In another embodiment, a new a new 6xxx aluminum alloy includes not greater than 0.08 wt. % Cr. In yet another embodiment, a new a new 6xxx aluminum alloy includes not greater than 0.06 wt. % Cr. In another embodiment, a new a new 6xxx aluminum alloy includes not greater than 0.05 wt. % Cr. In one embodiment, a new 6xxx aluminum alloy includes from 0.01 to 0.05 wt. % Cr.

[0011] The new 6xxx aluminum alloy may optionally include zirconium (Zr) and in an amount of up to 0.15 wt. % Zr (e.g., for grain structure control). In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.10 wt. % Zr. In another embodiment, a new a new 6xxx aluminum alloy includes not greater than 0.05 wt. % Zr. In yet another embodiment, a new a new 6xxx aluminum alloy includes not greater than 0.03 wt. % Zr. In another embodiment, a new a new 6xxx aluminum alloy includes not greater than 0.01 wt. % Zr.

[0012] The new 6xxx aluminum alloy may include up to 0.15 wt. % Ti. Titanium (Ti) may optionally be present in the new 6xxx aluminum alloy, such as for grain refining purposes. In one embodiment, a new 6xxx aluminum alloy includes at least 0.005 wt. % Ti. In another embodiment, a new 6xxx aluminum alloy includes at least 0.010 wt. % Ti. In yet another embodiment, a new 6xxx aluminum alloy includes at least 0.0125 wt. % Ti. In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.10 wt. % Ti. In another embodiment, a new 6xxx aluminum alloy includes not greater than 0.08 wt. % Ti. In yet

another embodiment, a new 6xxx aluminum alloy includes not greater than 0.05 wt. % Ti. In one embodiment, a target amount of titanium in a new 6xxx aluminum alloy is 0.03 wt. % Ti. In one embodiment, a new 6xxx aluminum alloy includes from 0.01 to 0.05 wt. % Ti.

[0013] Zinc (Zn) may optionally be present in the new 6xxx aluminum alloy, and in an amount up to 0.10 wt. % Zn. In one embodiment, a new alloy includes not greater than 0.05 wt. % Zn. In another embodiment, a new alloy includes not greater than 0.03 wt. % Zn. In another embodiment, a new alloy includes not greater than 0.01 wt. % Zn.

[0014] Vanadium (V) may optionally be present in the new 6xxx aluminum alloy, and in an amount of up to 0.05 wt. % V. In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.03 wt. % V. In another embodiment, a new 6xxx aluminum alloy includes not greater than 0.01 wt. % V.

[0015] As noted above, the balance of the new aluminum alloy is generally aluminum and impurities. In one embodiment, a new 6xxx aluminum alloy includes not greater than 0.15 wt. %, in total, of the impurities, and wherein the 6xxx aluminum alloy includes not greater than 0.05 wt. % of each of the impurities. In another embodiment, a new 6xxx aluminum alloy includes not greater than 0.10 wt. %, in total, of the impurities, and wherein the 6xxx aluminum alloy includes not greater than 0.03 wt. % of each of the impurities.

[0016] Except where stated otherwise, the expression “up to” when referring to the amount of an element means that that elemental composition is optional and includes a zero amount of that particular compositional component. Unless stated otherwise, all compositional percentages are in weight percent (wt. %).

ii. Processing and Product Forms

[0017] The new 6xxx alloys may be useful in a variety of product forms, including ingot or billet, wrought product forms (sheet, plate, forgings and extrusions), shape castings, additively manufactured products, and powder metallurgy products. In one embodiment, a new 6xxx aluminum alloy is a rolled product. For example, the new 6xxx aluminum alloys may be produced in sheet form. In one embodiment, a sheet made from the new 6xxx aluminum alloy has a thickness of from 1.5 mm to 4.0 mm.

[0018] In one embodiment, the new 6xxx aluminum alloys are produced using ingot casting and hot rolling. In one embodiment, a method includes the steps of casting an ingot of the new 6xxx aluminum alloy, homogenizing the ingot, rolling the ingot into a rolled product having a final gauge (via hot rolling and/or cold rolling), solution heat treating the rolled product, wherein the solution heat treating comprises heating the rolled product to a temperature and for

a time such that some or substantially all of Mg_2Si of the rolled product is dissolved into solid solution, and after the solution heat treating, quenching the rolled product (e.g., water or air quenching). After the quenching, the rolled product may be artificially aged. In some embodiments, one or more anneal steps may be completed before or after a rolling step (e.g., hot rolling to a first gauge, annealing, cold rolling to the final gauge). The artificially aged product can be painted (e.g., for an automobile part), and may thus be subjected to a paint-bake cycle. In one embodiment, the rolled aluminum alloy products produced from the new alloy may be incorporated in an automobile.

[0019] In one embodiment, the new 6xxx aluminum alloys products are cast via continuous casting. Downstream of the continuous casting, the product can be (a) rolled (hot and/or cold), (b) optionally annealed (e.g., after hot rolling and prior to any cold rolling steps), (c) solution heat treated and quenched, (d) optionally cold worked (post-solution heat treatment), and (e) artificially aged, and all steps (a) - (e) may occur in-line or off-line relative to the continuous casting step. Some methods for producing the new 6xxx aluminum alloys products using continuous casting and associated downstream steps are described in, for example, U.S. Patent No. 7,182,825, U.S. Patent Application Publication No. 2014/0000768, and U.S. Patent Application Publication No. 2014/036998, each of which is incorporated herein by reference in its entirety. The artificially aged product can be painted (e.g., for an automobile part), and may thus be subjected to a paint-bake cycle.

[0020] In one embodiment, the hot rolling comprises hot rolling to an intermediate gauge product, wherein the intermediate gauge product exits the hot rolling apparatus at a temperature of not greater than 290°C. After the hot rolling, an optional anneal may be completed. After the hot rolling and any anneal, the intermediate gauge product may be cold rolled to final gauge.

[0021] In another embodiment, the hot rolling comprises rolling to an intermediate gauge product, wherein the intermediate gauge product exits the hot rolling apparatus at a temperature of from 400-480°C. After the hot rolling, the intermediate gauge product may then be cold rolled to final gauge, i.e., no anneal is required after the hot rolling and prior to cold rolling in this embodiment.

[0022] When cold rolling is completed, the cold rolling generally comprises reducing the thickness of the intermediate gauge thickness to the final gauge thickness. In one embodiment, the cold rolling comprises cold rolling by at least 50%. In another embodiment, the cold rolling comprises cold rolling by at least 60%. In yet another embodiment, the cold rolling comprises cold rolling by at least 65%. In one embodiment, the cold rolling is not greater than 85%.

[0023] As known to those skilled in the art, "cold rolled XX %" and the like means $XX_{CR}\%$, where $XX_{CR}\%$ is the amount of thickness reduction achieved when the aluminum alloy body is reduced from a first thickness of T_1 to a second thickness of T_2 , where T_1 is the intermediate gauge thickness and wherein T_2 is the thickness. In other words, $XX_{CR}\%$ is equal to:

$$XX_{CR}\% = (1 - T_2/T_1) * 100\%$$

For example, when an aluminum alloy body is cold rolled from a first thickness (T_1) of 15.0 mm to a second thickness of 3.0 mm (T_2), $XX_{CR}\%$ is 80%. Phrases such as "cold rolling 80%" and "cold rolled 80%" are equivalent to the expression $XX_{CR}\% = 80\%$

[0024] In one embodiment, the peak metal temperature during solution heat treatment is in the range of from 504°C to 593°C. The peak metal temperature is the highest temperature realized by an alloy product during solution heat treatment.

[0025] In one embodiment, the new 6xxx aluminum alloy products are processed to a T4 temper as defined by ANSI H35.1 (2009), i.e., the new 6xxx are solution heat treated and then quenched and then naturally aged to a substantially stable condition. In one embodiment, the natural aging amount is 30 days and the T4 properties of the new 6xxx aluminum alloy are measured at 30 days of natural aging.

[0026] In one embodiment, the new 6xxx aluminum alloys are processed to a T6 temper as defined by ANSI H35.1 (2009), i.e., the new 6xxx are solution heat treated and then quenched and then artificially aged. In one embodiment, the artificial aging comprises paint baking. In one embodiment, the artificial aging consist of paint baking. In one embodiment, paint baking comprises heating the new 6xxx aluminum alloy product to 180°C and then holding for 20 minutes.

[0027] In one embodiment, the new 6xxx aluminum alloys are processed to a T8 temper as defined by ANSI H35.1 (2009), i.e., the new 6xxx are solution heat treated and then quenched and then cold worked (e.g., stretched), and then artificially aged. In one embodiment, the artificial aging comprises paint baking. In one embodiment, the artificial aging consist of paint baking. In one embodiment, paint baking comprises heating the new 6xxx aluminum alloy product to 180°C and then holding for 20 minutes.

iii. Microstructure

A. Recrystallization

[0028] The processing of the new 6xxx aluminum alloy steps may be accomplished such that a new aluminum alloy body product realizes a predominately recrystallized microstructure. A predominately recrystallized microstructure means that the aluminum alloy body contains at least 51% recrystallized grains (by volume fraction). The degree of recrystallization of a new

6xxx aluminum alloy product may be determined using appropriate metallographic samples of the material analyzed with EBSD by an appropriate SEM and computer software to determine intergranular misorientation. In one embodiment, a new 6xxx aluminum alloy product is at least 60% recrystallized. In another embodiment, a new 6xxx aluminum alloy product is at least 70% recrystallized. In yet another embodiment, a new 6xxx aluminum alloy product is at least 80% recrystallized. In another embodiment, a new 6xxx aluminum alloy product is at least 90% recrystallized. In yet another embodiment, a new 6xxx aluminum alloy product is at least 95% recrystallized. In another embodiment, a new 6xxx aluminum alloy product is at least 98% recrystallized, or more.

B. Grain Size and Texture

[0029] A new 6xxx aluminum alloy product may realize a fine grain size. In one embodiment, a new 6xxx aluminum alloy product realizes an area weighted average grain size of not greater than 45 micrometers. In another embodiment, a new 6xxx aluminum alloy product realizes an area weighted average grain size of not greater than 40 micrometers. In one embodiment, a new 6xxx aluminum alloy product realizes an area weighted average grain size of at least 20 micrometers. In another embodiment, a new 6xxx aluminum alloy product realizes an area weighted average grain size of at least 25 micrometers. In yet another embodiment, a new 6xxx aluminum alloy product realizes an area weighted average grain size of at least 30 micrometers.

[0030] A new 6xxx aluminum alloy product may realize a unique texture. Texture means a preferred orientation of at least some of the grains of a crystalline structure. Using matchsticks as an analogy, consider a material composed of matchsticks. That material has a random texture if the matchsticks are included within the material in a completely random manner. However, if the heads of at least some of those matchsticks are aligned in that they point the same direction, like a compass pointing north, then the material would have at least some texture due to the aligned matchsticks. The same principles apply with grains of a crystalline material.

[0031] Texture components resulting from production of aluminum alloy products may include one or more of copper, S texture, brass, cube, and Goss texture, to name a few. Each of these texture components is defined in Table 1, below.

Table 1

Texture component	Miller Indices	Bunge ($\phi 1$, Φ , $\phi 2$)	Kocks (Ψ , Θ , Φ)
copper	$\{112\}\langle 11\bar{1}\rangle$	90, 35, 45	0, 35, 45
S	$\{123\}\langle 63\bar{4}\rangle$	59, 37, 63	149, 37, 27
brass	$\{110\}\langle \bar{1}12\rangle$	35, 45, 0	55, 45, 0
Cube	$\{100\}\langle 001\rangle$	0, 0, 0	0, 0, 0
Goss	$\{110\}\langle 001\rangle$	0, 45, 0	0, 45, 0

[0032] The below table is a non-limiting example of texture components and ranges that may be realized by the new 6xxx aluminum alloys disclosed herein.

Texture Type	Min (%)	(Max (%))
Cube	10	25
Goss	0	2.0
Brass	0	1.5
S	0	3.0
Copper	0	2.5

[0033] For purposes of the present patent application grain size and texture are to be measured and normalized as follows:

- A Phillips XL-30 FESEM or equivalent is to be used.
- Electron backscatter diffraction (EBSD) patterns are to be collected using an EDAX EBSD Digiview 5 detection system, or equivalent. The EBSD acquisition is to be performed using EDAX TSL EBSD Data Collection (OIM)TM software, version 7, or equivalent.
- Samples are to be cross-sectioned and polished for analysis of the longitudinal (L) x short transverse (ST) plane, and prepared for standard metallographic analysis, e.g., by grinding the cross-sectioned and mounted sample flat and polishing with successively finer grits to 0.05 μm colloidal silica (SiO_2). The final step is vibratory polishing for 45 minutes.
- After metallographic preparation, the samples are to be ion milled for 15 minutes using an appropriate broad beam argon ion milling system (e.g., an Hitachi

IM4000Plus) operated at 3kV and glancing angle incidence (10 degrees) on the sample surface, while the sample is rotated at 25 rotations per minute.

- Data acquisition parameters are to include an electron beam energy of 20kV, a spot size 5 with a sample tilt angle of 70 degrees; a 0.8 micrometer step size and square grid scan type are to be used.
- EBSD patterns are to be collected using 8x8 binning and enhanced image processing, including background subtraction and a normalized intensity histogram. Map dimensions are to be full thickness in the short transverse (ST) direction by 800 micrometers in the longitudinal (L) direction (i.e., the rolling direction for sheet products).
- The software used to analyze the acquired data should be an EDAX TSL OIM™ 8 data analysis package or similar. Data analysis included a 2-step clean-up procedure. The first step is a Neighbor Orientation Correlation level 2 clean up applied to data with a minimum confidence index (CI) of 0.1 and grain tolerance angle of 5 degrees. The second step is a Grain Dilation using a grain tolerance angle of 5 degrees and a minimum of 5 points per grain for a single iteration.
- Grains are defined to have a minimum of 5 points per grain with a grain tolerance angle of 5 degrees. In one embodiment, the software determines grain size (average grain diameter) via the Heyn linear intercept method, generally as per ASTM E112-12, § 13.
- In another embodiment, individual grain sizes are determined by counting the number of points within each grain and multiplying by the area of each point (step size squared).
- The following equation may be used to calculate grain size (i.e., equivalent circular diameter):

$$v_i = \text{square root} \left(\frac{4A_i}{\pi} \right)$$

where A_i is the area of each individual grain as measured per above. “ v_i ” is the calculated individual grain size assuming the grain is a circle. The number average grain size, $\bar{v}_n$, is the arithmetic mean of v_i .

$$\bar{v}_n = \left(\sum_{i=1}^n v_i \right) / n$$

- The “area weighted average grain size” may be calculated using the following equation:

$$\bar{v}_a = (\sum_{i=1}^n A_i v_i) / (\sum_{i=1}^n A_i)$$

where A_i is the area of each individual grain, as per above, and where v_i is the calculated individual grain size, as per above. “ $\bar{v}_a$ ” is the area weighted average grain size.

- The quantification of texture components present (Cube%, Goss%, Brass%, S%, Copper%) is to be determined as the number fraction of measured points assigned to a specific texture component. Points are assigned to a texture component if the misorientation angle deviates from the ideal orientation by less than 13.74 degrees. This number fraction is multiplied by 100 to find the percentage of each texture component in the sample.

iv. Properties

[0034] As noted above, the new 6xxx aluminum alloys disclosed herein may realize an improved combination of properties. In one embodiment, a new 6xxx aluminum alloy realizes a T4 tensile yield strength in the LT (long transverse) direction of from 90 to 110 MPa. In one embodiment, a new 6xxx aluminum alloy realizes a T4 uniform elongation in the LT (long transverse) direction of at least 21%. In one embodiment, a new 6xxx aluminum alloy realizes a T4 n value (10-20%) in the LT (long transverse) direction of at least 0.245. For purposes of this paragraph, T4 properties are to be measured after 30 days of natural aging.

[0035] For purposes of this patent application, tensile yield strength and uniform elongation are to be measured in accordance with ASTM E8 and B557. For purposes of this patent application, “n value (10-20%)” is to be measured in accordance with ASTM E646 using 10-20% strain.

[0036] In one embodiment, a new 6xxx aluminum alloy realizes a T6 (0% pre-strain/stretch) tensile yield strength of at least 160 MPa when artificially aged by paint baking at 180°C for 20 minutes. In another embodiment, a new 6xxx aluminum alloy realizes a T6, (0% pre-strain/stretch) tensile yield strength of at least 170 MPa when artificially aged by paint baking at 180°C for 20 minutes. In yet another embodiment, a new 6xxx aluminum alloy realizes a T6 (0% pre-strain/stretch) tensile yield strength of at least 180 MPa when artificially aged by paint baking at 180°C for 20 minutes.

[0037] In one embodiment, a new 6xxx aluminum alloy realizes a T8 tensile yield strength of at least 215 MPa when post-SHT stretched 1-3 % and then artificially aged by paint baking at 180°C for 20 minutes.

[0038] In one embodiment, a new 6xxx aluminum alloy realizes a Hem rating of 2 or better. Hem rating is defined in the below Examples. In another embodiment, a new 6xxx aluminum alloy realizes a Hem rating of 1.

[0039] In one embodiment, a new 6xxx aluminum alloy realizes a VDA bend angle of at least 125°. VDA testing is to be tested by natural aging the product for 30 days, and then stretching the product 10% in the L (longitudinal) direction, and then conducting the VDA bend test in accordance with the VDA 238-100 bend test specification. (<https://www.vda.de/en/services/Publications/vda-238-100-plate-bending-test-for-metallic-materials.html>). In another embodiment, a new 6xxx aluminum alloy realizes a VDA bend angle of at least 130°. In yet another embodiment, a new 6xxx aluminum alloy realizes a VDA bend angle of at least 135°. In another embodiment, a new 6xxx aluminum alloy realizes a VDA bend angle of at least 140°. In yet another embodiment, a new 6xxx aluminum alloy realizes a VDA bend angle of at least 143°.

[0040] In one embodiment, a new 6xxx aluminum alloy is absent of Ludering. Ludering is to be tested by naturally aging the product for 8 days, and then stretching the product 10% in the L (longitudinal) direction. If Luder lines are visible to the naked eye, the product is not absent of Ludering. If Luder lines are invisible to the naked eye, the product is absent of Ludering.

[0041] In one embodiment, a new 6xxx aluminum alloy realizes a combination of properties shown in the “Preferred Property Box” of FIG. 1. In some of these embodiments, a new 6xxx aluminum alloy realizes a VDA bend angle of at least 140°. Others of the above-identified properties may also be realized.

[0042] In one embodiment, a new 6xxx aluminum alloy realizes a combination of properties shown in the “Preferred Property Box” of FIG. 2. In some of these embodiments, a new 6xxx aluminum alloy realizes a VDA bend angle of at least 140°. Others of the above-identified properties may also be realized.

[0043] In one embodiment, a new 6xxx aluminum alloy realizes a combination of properties shown in the “Preferred Property Box” of FIG. 3. In some of these embodiments, a new 6xxx aluminum alloy realizes a VDA bend angle of at least 140°. Others of the above-identified properties may also be realized.

[0044] In one embodiment, a new 6xxx aluminum alloy realizes a combination of properties shown in the “Preferred Property Box” of FIG. 4. In some of these embodiments, a new 6xxx aluminum alloy realizes a VDA bend angle of at least 140°. Others of the above-identified properties may also be realized.

[0045] The figures constitute a part of this specification and include illustrative embodiments of the present invention and illustrate various objects and features thereof. In addition, any measurements, specifications and the like shown in the figures are intended to be illustrative, and not restrictive. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present invention.

[0046] The various embodiments to the present disclosure will be further explained with reference to the attached drawings, wherein like structures are referred to by like numerals throughout the several views. The drawings shown are not necessarily to scale, with emphasis instead generally being placed upon illustrating the principles of the present invention. Further, some features may be exaggerated to show details of particular components.

[0047] Among those benefits and improvements that have been disclosed, other objects and advantages of this invention will become apparent from the following description taken in conjunction with the accompanying figures. Detailed embodiments of the present invention are disclosed herein; however, it is to be understood that the disclosed embodiments are merely illustrative of the invention that may be embodied in various forms. In addition, each of the examples given in connection with the various embodiments of the invention is intended to be illustrative, and not restrictive.

[0048] Throughout the specification and claims, the following terms take the meanings explicitly associated herein, unless the context clearly dictates otherwise. The phrases “in one embodiment” and “in some embodiments” as used herein do not necessarily refer to the same embodiment(s), though they may. Furthermore, the phrases “in another embodiment” and “in some other embodiments” as used herein do not necessarily refer to a different embodiment, although they may. Thus, as described below, various embodiments of the invention may be readily combined, without departing from the scope or spirit of the invention.

[0049] In addition, as used herein, the term “or” is an inclusive “or” operator, and is equivalent to the term “and/or,” unless the context clearly dictates otherwise. The term “based on” is not exclusive and allows for being based on additional factors not described, unless the context clearly dictates otherwise. In addition, throughout the specification, the meaning of “a,” “an,” and “the” include plural references, unless the context clearly dictates otherwise. The meaning of “in” includes “in” and “on”, unless the context clearly dictates otherwise.

BRIEF DESCRIPTION OF THE DRAWINGS

[0050] FIG. 1 is an image of the grain structure of alloy A1-1.

[0051] FIG. 2 is an image of the grain structure of alloy A1-10.

[0052] FIG. 3 is an image of the grain structure of alloy A1-19.

[0053] FIG. 4 is an image of the grain structure of alloy A1-22.

[0054] FIG. 5 is a graph illustrating the tensile yield strength (after paint bake, no pre-strain, i.e., T6) versus n value (10-20%) in the as is (T4) temper for various example alloys.

[0055] FIG. 6 is a graph illustrating the tensile yield strength (after paint bake, no pre-strain, i.e., T6) versus uniform elongation in the as is (T4) temper for various example alloys.

[0056] FIG. 7 is a graph illustrating the tensile yield strength (after paint bake, 2% pre-strain, i.e., T8) versus n value (10-20%) in the as is (T4) temper for various example alloys.

[0057] FIG. 8 is a graph illustrating the tensile yield strength (after paint bake, 2% pre-strain, i.e., T8) versus uniform elongation in the as is (T4) temper for various example alloys.

DETAILED DESCRIPTION

[0058] The following examples are intended to illustrate the invention and should not be construed as limiting the invention in any way.

Example 1: Alloy Composition

[0059] Aluminum alloys having the compositions shown in Table 1, below, were cast as ingots.

Table 1: Compositions of Example 1 Alloys (wt. %)

Sample	Si	Fe	Cu	Mn	Mg	Cr	Ti	Zn	Bal.
Alloy A1 (inv.)	0.74	0.18	0.13	0.07	0.52	0.03	0.03	0.005	Al + Imp.
Alloy A2 (inv.)	0.76	0.14	0.13	0.07	0.54	0.03	0.03	0.007	Al + Imp.
Alloy B1 (non-inv.)	0.63	0.21	0.13	0.07	0.60	0.03	0.02	0.004	Al + Imp.

[0060] The ingots were then homogenized and then hot rolled to an intermediate gauge with an exit temperature of not greater than 290 °C. The alloys were then cold rolled to a final gauge of 0.95 or 1.2 mm. The cold rolling amounts (reduction from the intermediate gauge to the final gauge) are provided in Table 2, below. The final gauge products were then solution heat treated by heating to various peak metal temperatures (shown in Table 2), after which the alloys were immediately air quenched. After quenching, some alloys were then stretched while others were not, as shown in Table 2. All alloys were then naturally aged for 30 days, after which some alloys were then stretched, and after which some alloys (both stretched and non-

stretched) were artificially aged by heating to 180°C and then holding at this temperature for 20 minutes, and then cooling to room temperature. The 2% stretching (pre-strain) was completed in the lab and simulates a typical forming operation.

[0061] Mechanical properties of the alloys in various tempers (T4, T6, T8) were then measured, the results of which are provided in Table 3, below. Mechanical properties were tested according to ASTM E8, ASTM B557. All reported mechanical property values are for the LT (long-transverse) direction, and based on the average of 6 specimens, unless otherwise indicated. The “n value” was measured in accordance ASTM E646 using 10-20% strain.

Table 2: Processing of Example 1 Alloys

Alloy Number	Cold Work (% reduction)	Final Gauge (mm)	Peak Metal Temperature (°C)	Stretch (%)	Artificial Aging (min at 185°C)
A1-1	82%	0.95	552	0%	0
A1-2	82%	0.95	539	0%	0
A1-3	82%	0.95	533	0%	0
A1-4	82%	0.95	552	0%	20
A1-5	82%	0.95	539	0%	20
A1-6	82%	0.95	533	0%	20
A1-7	82%	0.95	552	2%	20
A1-8	82%	0.95	539	2%	20
A1-9	82%	0.95	533	2%	20
A1-10	81%	1.20	552	0%	0
A1-11	81%	1.20	539	0%	0
A1-12	81%	1.20	533	0%	0
A1-13	81%	1.20	552	0%	20
A1-14	81%	1.20	539	0%	20
A1-15	81%	1.20	533	0%	20
A1-16	81%	1.20	552	2%	20
A1-17	81%	1.20	539	2%	20
A1-18	81%	1.20	533	2%	20
A1-19	72%	0.95	552	0%	0
A1-20	72%	0.95	539	0%	0
A1-21	72%	0.95	533	0%	0
A1-22	65%	1.20	552	0%	0
A1-23	65%	1.20	539	0%	0
A1-24	65%	1.20	533	0%	0
A2-1	82%	0.95	552	0%	0
A2-2	82%	0.95	539	0%	0
A2-3	82%	0.95	533	0%	0

Alloy Number	Cold Work (% reduction)	Final Gauge (mm)	Peak Metal Temperature (°C)	Stretch (%)	Artificial Aging (min at 185°C)
A2-4	82%	0.95	552	0%	20
A2-5	82%	0.95	539	0%	20
A2-6	82%	0.95	533	0%	20
A2-7	82%	0.95	552	2%	20
A2-8	82%	0.95	539	2%	20
A2-9	82%	0.95	533	2%	20
A2-10	81%	1.20	552	0%	0
A2-11	81%	1.20	539	0%	0
A2-12	81%	1.20	533	0%	0
A2-13	81%	1.20	552	0%	20
A2-14	81%	1.20	539	0%	20
A2-15	81%	1.20	533	0%	20
A2-16	81%	1.20	552	2%	20
A2-17	81%	1.20	539	2%	20
A2-18	81%	1.20	533	2%	20
A2-19	72%	0.95	552	0%	0
A2-20	72%	0.95	539	0%	0
A2-21	72%	0.95	533	0%	0
A2-22	65%	1.20	552	0%	0
A2-23	65%	1.20	539	0%	0
A2-24	65%	1.20	533	0%	0
B1-1	82%	0.95	552	0%	0
B1-2	82%	0.95	539	0%	0
B1-3	82%	0.95	533	0%	0
B1-4	82%	0.95	552	0%	20
B1-5	82%	0.95	539	0%	20
B1-6	82%	0.95	533	0%	20
B1-7	82%	0.95	552	2%	20
B1-8	82%	0.95	539	2%	20
B1-9	82%	0.95	533	2%	20
B1-10	81%	1.20	552	0%	0
B1-11	81%	1.20	539	0%	0
B1-12	81%	1.20	533	0%	0
B1-13	81%	1.20	552	0%	20
B1-14	81%	1.20	539	0%	20
B1-15	81%	1.20	533	0%	20
B1-16	81%	1.20	552	2%	20
B1-17	81%	1.20	539	2%	20
B1-18	81%	1.20	533	2%	20

Table 3: Tensile Properties of Various Example 2 Alloys

Alloy Number	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Ultimate Elongation (%)	Tensile Elongation (%)	n Value (10-20%)
A1-1	108	218	22.1	26.3	0.25
A1-2	105	213	20.7	23.9	0.244
A1-3	101	208	21.3	25.5	0.24
A1-4	187	274	18.1	22.7	0.185
A1-5	178	264	17.8	22	0.182
A1-6	173	258	17.7	22.6	0.178
A1-7	220	286	16.3	20.3	0.164
A1-8	216	278	15.3	19	0.155
A1-9	208	271	15.1	19.1	0.154
A1-10	110	217	21.7	26.3	0.245
A1-11	104	210	21	25.4	0.239
A1-12	98	201	19.6	22.7	0.238
A1-13	189	273	17.9	23.3	0.179
A1-14	182	265	17.1	21.7	0.174
A1-15	168	251	15.9	20.7	0.175
A1-16	222	285	15.9	20.1	0.157
A1-17	212	275	15.4	19.3	0.156
A1-18	201	263	14	17.5	0.152
A1-19	106	216	22.4	26	0.258
A1-20	103	211	22	25.4	0.252
A1-21	100	207	21.2	25.4	0.249
A1-22	108	216	22.3	26.5	0.253
A1-23	103	207	20.3	26.3	0.248
A1-24	96	200	21.2	24.8	0.245
A2-1	113	225	22.4	27.0	0.255
A2-2	110	219	21.6	25.7	0.248
A2-3	105	212	20.5	22.0	0.244
A2-4	194	280	18.6	23.3	0.186
A2-5	192	276	17.9	22.5	0.181
A2-6	188	272	17.2	22.0	0.174
A2-7	227	292	16.4	20.8	0.165
A2-8	221	285	15.5	19.8	0.161
A2-9	220	281	14.3	17.0	0.153
A2-10	114	223	21.2	25.5	0.247
A2-11	107	214	21.0	25.2	0.241
A2-12	101	205	20.4	24.3	0.239
A2-13	196	279	17.6	22.3	0.179
A2-14	186	268	17.0	21.6	0.175

Alloy Number	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Ultimate Elongation (%)	Tensile Elongation (%)	n Value (10-20%)
A2-15	173	255	16.3	20.5	0.173
A2-16	226	289	15.9	20.3	0.160
A2-17	214	277	15.5	18.7	0.159
A2-18	201	264	14.9	18.9	0.155
A2-19	112	223	23.1	27.0	0.264
A2-20	109	218	22.4	26.2	0.257
A2-21	104	212	22.3	26.2	0.253
A2-22	113	225	22.4	27.0	0.255
A2-23	110	219	21.6	25.7	0.248
A2-24	105	212	20.5	22.0	0.244
B1-1	107	215	20.7	25	0.242
B1-2	101	207	20.8	25	0.236
B1-3	93	196	19.9	23.3	0.233
B1-4	176	264	18.1	22.6	0.187
B1-5	171	256	16.9	21.3	0.178
B1-6	156	242	16.6	20.2	0.179
B1-7	211	278	15.6	20.3	0.162
B1-8	202	267	15.6	20.1	0.157
B1-9	189	254	14.8	18.1	0.155
B1-10	107	213	20.8	24.3	0.239
B1-11	98	201	20.7	24.6	0.234
B1-12	88	188	20.4	24.9	0.23
B1-13	177	262	17.5	22.3	0.181
B1-14	163	249	16.7	20.3	0.18
B1-15	141	226	14.7	17.4	0.183
B1-16	210	273	15.4	20.1	0.158
B1-17	195	259	14.6	17.9	0.157
B1-18	172	235	13.1	16.2	0.155

[0062] For all processing conditions, the invention alloys achieved higher tensile yield strengths (TYS) and ultimate yield strengths (UTS) than non-invention alloys. Further, the invention alloys showed less strength loss at lower peak metal temperatures. The invention alloys also generally had higher elongation and higher n values over non-invention alloys at most processing conditions, indicating improved formability.

Example 2: Hem Performance Testing

[0063] Select Example 1 alloys were tested for hemming performance by stretching them 15% in the L direction after which a flat hem test was performed. The stretching was completed on alloys that had been naturally aged for 30 days and without subsequent artificial aging, i.e., the alloys were in a T4 temper prior to the 15% stretching. Four hems were completed for each processing condition. The hem ratings were then evaluated per the below scale.

Hem Rating Scale	
1 or 2	Mild (1) to moderate (2) orange peel with no cracking visible at 3x magnification
3	Crack(s) visible with 3x magnification
4	Cracks visible with naked eye

Table 4, below, shows the achieved hem ratings for A1 and A2 alloys.

Table 4: Hem Ratings of Select Example 2 Alloys

Alloy Number	Hem rating (1-4)		Alloy Number	Hem rating (1-4)
A1-1	2		A2-1	2
A1-2	2		A2-2	2
A1-3	2		A2-3	2
A1-10	2		A2-10	2
A1-11	2		A2-11	2
A1-12	2		A2-12	2
A1-19	2		A2-19	2
A1-20	2		A2-20	2
A1-21	2		A2-21	2
A1-22	2		A2-22	3
A1-23	2		A2-23	3
A1-24	2		A2-24	3

[0064] A1 alloys have more iron than A2 alloys. Those in industry have associated higher iron content to poorer hemming performance. However, the A1 alloys demonstrated better hemming performance than the A2 alloys. Further, higher iron content improved hemming performance in samples with lower levels of cold working (e.g. alloys A1-22, A1-23 and A1-24 had 65% cold work and demonstrated the same hemming performance as alloys A1-10, A1-11 and A1-12, which were the same gauge but only 81% cold work).

Example 3: VDA Bend Performance Testing

[0065] Select Example 1 were stretched 10% in the L direction and tested per the VDA 238-100 bend test specification. (<https://www.vda.de/en/services/Publications/vda-238-100-plate-bending-test-for-metallic-materials.html>) VDA stands for “Verband der Automobilindustrie”. The stretching was completed on alloys that has been naturally aged for 30 days and without subsequent artificial aging, i.e., the alloys were in a T4 temper prior to the 10% stretching. Table 5, below, shows the VDA bend test results for select Example 2 alloys.

Table 5: VDA Bend Test Results of select Example 2 Alloys

Alloy Number	VDA Bend Angle (°)		Alloy Number	VDA Bend Angle (°)
A1-10	140		A2-10	140
A1-11	142		A2-11	141
A1-12	143		A2-12	143
A1-22	129		A2-22	127
A1-23	133		A2-23	127
A1-24	137		A2-24	129

[0066] At 65% cold work the A1 alloys demonstrated improved bending over the A2 alloys. It is believed that at least the difference in iron content contributed to this difference in properties. (A difference of 2° is a material difference at these levels of achieved bend angle.)

Example 4: Ludering

[0067] Select samples of Example 1 alloys were naturally aged 8 days and then stretched 10% in the LT direction, after which a coating of paint was applied. After painting, the alloys were examined to determine if Luder bands were present. Table 6, below, shows the tensile yield strength and Luder band results for select Example 2 alloys.

Table 6: Ludering Results of Select Example 1 Alloys

Alloy Number	TYS (MPa)	Ludering Present
A1-1	108	No
A1-2	105	No
A1-3	101	No
A1-10	108	No
A1-11	103	No
A1-12	96	No

Alloy Number	TYS (MPa)	Ludering Present
A1-13	106	No
A1-14	103	No
A1-15	100	No
A1-19	110	No
A1-20	104	No
A1-21	98	No
B1-1	107	No
B1-2	98	No
B1-3	88	Yes
B1-10	107	No
B1-11	101	Yes
B1-12	93	Yes

[0068] As shown in Table 6, only non-invention alloys showed the presence of Luder bands. For a range of alloy processing, invention alloys did not have any Luder bands present.

Example 5: Texture and grain size

[0069] Grain size and texture measurements of select A1 samples from Example 2 were obtained via electron backscattering detection in a scanning electron microscope. The results of the grain size and texture measurements are shown in Table 7, below. Further, grain structure images obtained via SEM are shown in FIGS. 1-4.

Table 7: Grain Size and Texture Values for select Example 2 alloys

	Alloy Number	A1-10	A1-22
	Gauge (mm)	1.2	1.2
	Cold Work (%)	81	65
Grain Size	Grain Size Via Intercept Method (μm)	18.6	23.2
	Grain Size Number Ave. (μm)	20.6	25
	Grain Size Area Ave. (weighted) (μm)	32.1	40.9
Texture	Cube %	21.8	14.97
	Goss %	1.99	1.8
	Brass %	0.98	0.81
	S %	2.26	2.78
	Copper %	1.98	2.27

[0070] Table 7 show that with higher levels of cold working, the A1 alloys have finer (smaller) grain structure and higher levels of Cube texture. FIGS. 1-4 show the grain structure images obtained via SEM for alloys A1-1, A1-10, A1-19, and A1-22. The weighted average grain sizes obtained from these images for alloys A1-1, A1-10, A1-19, and A1-22 were 32 μm , 32 μm , 34 μm , and 41 μm , respectively. Again, with higher levels of cold working, the A1 alloy have finer (smaller) grain structure. When invention and non-invention alloys of the same processing were compared for grain size measurements, alloy A1-1 had a coarser grain structure than alloy B1-1.

[0071] Thus, in some embodiments, the new alloys disclosed herein may have grain size area weighted average of from 20 micrometers to 45 micrometers. In one embodiment, the new alloys have a grain size of from 30 to 40 micrometers.

[0072] In some embodiments, the new alloys disclosed herein may be in sheet form and have the following texture characteristics:

Texture Type	Min (%)	(Max (%))
Cube	10	25
Goss	0	2.0
Brass	0	1.5
S	0	3.0
Copper	0	2.5

[0073] While various embodiments of the present disclosure have been described in detail, it is apparent that modifications and adaptations of those embodiments will occur to those skilled in the art. However, it is to be expressly understood that such modifications and adaptations are within the spirit and scope of the present disclosure.

CLAIMS**What is claimed is:**

1. A 6xxx aluminum alloy comprising:
 - 0.65 - 0.85 wt. % Si;
 - 0.40 - 0.59 wt. % Mg;
 - wherein (wt. % Mg) / (wt. % Si) is from 0.47 to 0.90;
 - 0.05 - 0.35 wt. % Fe;
 - 0.04 - 0.13 wt. % Mn;
 - 0 - 0.20 wt. % Cu;
 - 0 - 0.15 wt. % Cr;
 - 0 - 0.15 wt. % Zr;
 - 0 - 0.15 wt. % Ti;
 - 0 - 0.10 wt. % Zn;
 - 0 - 0.05 wt. % V;
 - the balance being aluminum and impurities.
2. The 6xxx aluminum alloy of claim 1, wherein the 6xxx aluminum alloy includes at least 0.675 wt. % Si, or at least 0.70 wt. % Si.
3. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.825 wt. % Si, or not greater than 0.80 wt. % Si.
4. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes at least 0.425 wt. % Mg, or at least 0.45 wt. % Mg, 0.475 wt. % Mg, or at least 0.50 wt. % Mg.
5. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.57 wt. % Mg.
6. The 6xxx aluminum alloy of any of the preceding claims, wherein the (wt. % Mg) / (wt. % Si) is at least 0.50, or at least 0.52, or at least 0.54, or at least 0.56, or at least 0.58, or at least 0.60.
7. The 6xxx aluminum alloy of any of the preceding claims, wherein the (wt. % Mg) / (wt. % Si) is not greater than 0.88, or not greater than 0.86, or not greater than 0.84, or not greater than 0.82.
8. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes at least 0.08 wt. % Fe.
9. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.32 wt. % Fe, or not greater than 0.28 wt. % Fe, or not greater

than 0.26 wt. % Fe.

10. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes at least 0.02 wt. % Cu, or at least 0.04 wt. % Cu, or at least 0.06 wt. % Cu, or at least 0.07 wt. % Cu, or at least 0.08 wt. % Cu, or at least 0.09 wt. % Cu.

11. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.19 wt. % Cu, or not greater than 0.18 wt. % Cu, or not greater than 0.17 wt. % Cu.

12. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes at least 0.05 wt. % Mn or at least 0.06 wt. % Mn.

13. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.12 wt. % Mn or not greater than 0.11 wt. % Mn, or not greater than 0.10 wt. % Mn.

14. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes at least 0.01 wt. % Cr, or at least 0.02 wt. % Cr.

15. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.10 wt. % Cr, or not greater than 0.08 wt. % Cr, or not greater than 0.06 wt. % Cr, or not greater than 0.05 wt. % Cr.

16. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.10 wt. % Zr, or not greater than 0.05 wt. % Zr, or not greater than 0.03 wt. % Zr, or not greater than 0.01 wt. % Zr.

17. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.10 wt. % Ti, or not greater than 0.08 wt. % Ti, or not greater than 0.05 wt. % Ti.

18. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.05 wt. % Zn, or not greater than 0.03 wt. % Zn, or not greater than 0.01 wt. % Zn.

19. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.03 wt. % V, or not greater than 0.01 wt. % V.

20. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.15 wt. %, in total, of the impurities, and wherein the 6xxx aluminum alloy includes not greater than 0.05 wt. % of each of the impurities.

21. The 6xxx aluminum alloy of any of the preceding claims, wherein the 6xxx aluminum alloy includes not greater than 0.10 wt. %, in total, of the impurities, and wherein the 6xxx aluminum alloy includes not greater than 0.03 wt. % of each of the impurities.

22. A 6xxx aluminum alloy comprising:

0.70 - 0.80 wt. % Si;

0.49 - 0.59 wt. % Mg;

wherein (wt. % Mg) / (wt. % Si) is from 0.61 to 0.84;

0.09 - 0.29 wt. % Fe;

0.06 - 0.10 wt. % Mn;

0.09 - 0.17 wt. % Cu;

0.01 - 0.05 wt. % Cr;

0.01 - 0.05 wt. % Ti;

not greater than 0.05 wt. % Zn;

not greater than 0.05 wt. % V;

not greater than 0.05 wt. % Zr;

the balance being aluminum and impurities.

23. A method comprising:

(a) casting the 6xxx aluminum alloy of any of claims 1-22 as a cast product;

(b) hot rolling the cast product to an intermediate gauge product, wherein either:

(i) an exit temperature of the intermediate gauge product is not greater than 290°C and wherein an anneal of the intermediate gauge product is completed after the hot rolling; or

(ii) an exit temperature of the intermediate gauge product is from 400 to 480°C;

(c) cold rolling the intermediate gauge product to a final gauge product;

wherein the intermediate gauge product has an as-received thickness;

wherein the final gauge product has a final thickness;

wherein the cold rolling comprises reducing the as-received thickness by at least 50% to achieve the final thickness.

24. The method of claim 23, comprising:

after the cold rolling, solution heat treating and then quenching the final gauge product;

wherein the solution heat treating comprises heating the final gauge product to a peak metal temperature;

wherein the peak metal temperature is not greater than 593°C.

25. The method of claim 24, comprising:

after the quenching, artificially aging the final gauge product.

26. The method of claim 24, wherein the artificial aging comprises paint baking.
27. The method of claim 23, comprising:
after the quenching, natural aging the final gauge product for at least 3 days.
28. The method of claim 23, wherein the final gauge product realizes a predominately recrystallized microstructure.
29. The method of claim 28, wherein the final gauge product realizes an area weighted average grain size of not greater than 45 micrometers, or not greater than 40 micrometers.
30. The method of claim 29, wherein the final gauge product realizes an area weighted average grain size of at least 20 micrometers, or at least 25 micrometers, or at least 30 micrometers.
31. The method of claim 28, wherein the final gauge product comprises at least 10% Cube texture.
32. A 6xxx aluminum alloy sheet product comprising:
0.65 - 0.85 wt. % Si;
0.40 - 0.59 wt. % Mg;
wherein (wt. % Mg) / (wt. % Si) is from 0.47 to 0.90;
0.05 - 0.35 wt. % Fe;
0.04 - 0.13 wt. % Mn;
0 - 0.20 wt. % Cu;
0 - 0.15 wt. % Cr;
0 - 0.15 wt. % Zr;
0 - 0.15 wt. % Ti;
0 - 0.10 wt. % Zn;
0 - 0.05 wt. % V;
the balance being aluminum and impurities;
wherein the 6xxx aluminum alloy sheet product has a thickness of from 1.5 to 4.0 mm;
wherein the 6xxx aluminum alloy sheet product has a predominately recrystallized microstructure;
wherein the 6xxx aluminum alloy sheet product realizes a weighted average grain size of from 5 to 45 micrometers; and
wherein the 6xxx aluminum alloy sheet product comprises at least 10% Cube texture.

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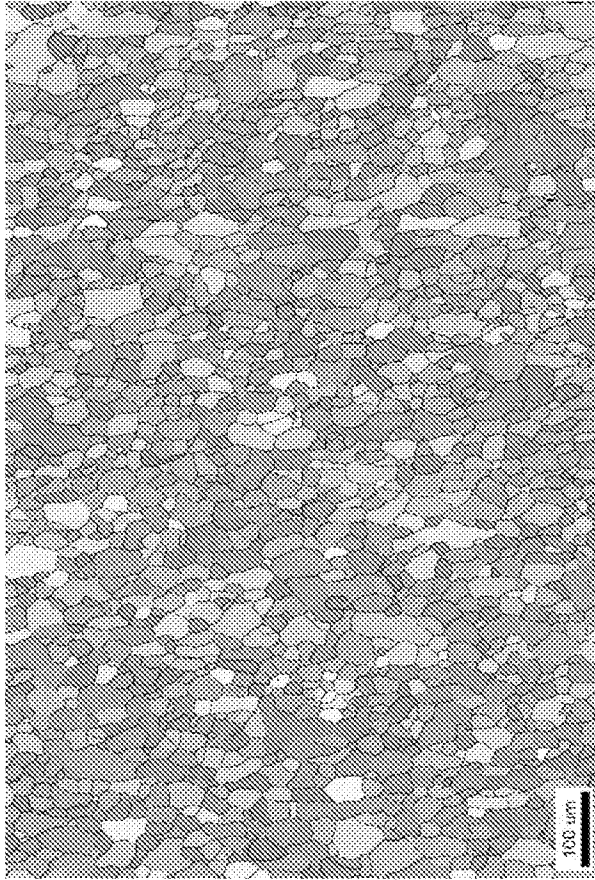


FIG. 2: Alloy A1-10.

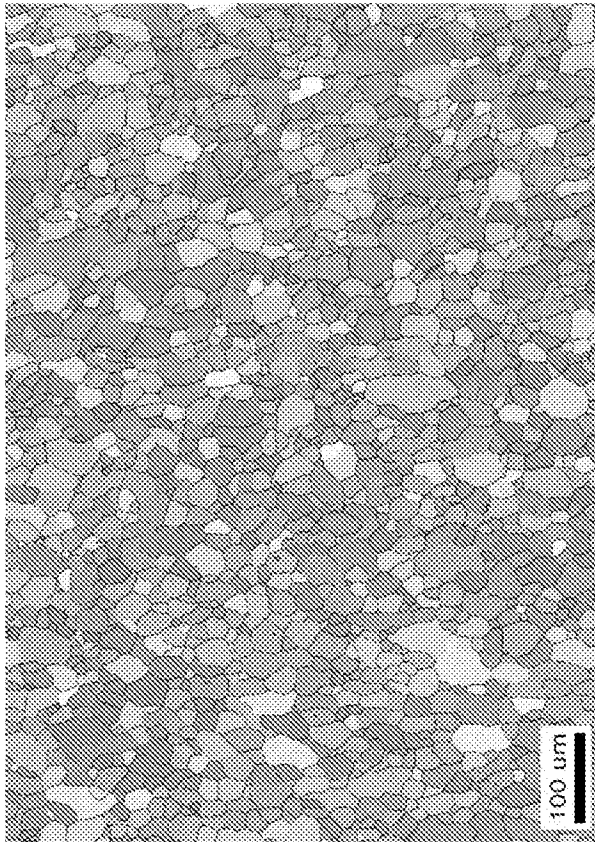


FIG. 1: Alloy A1-1.

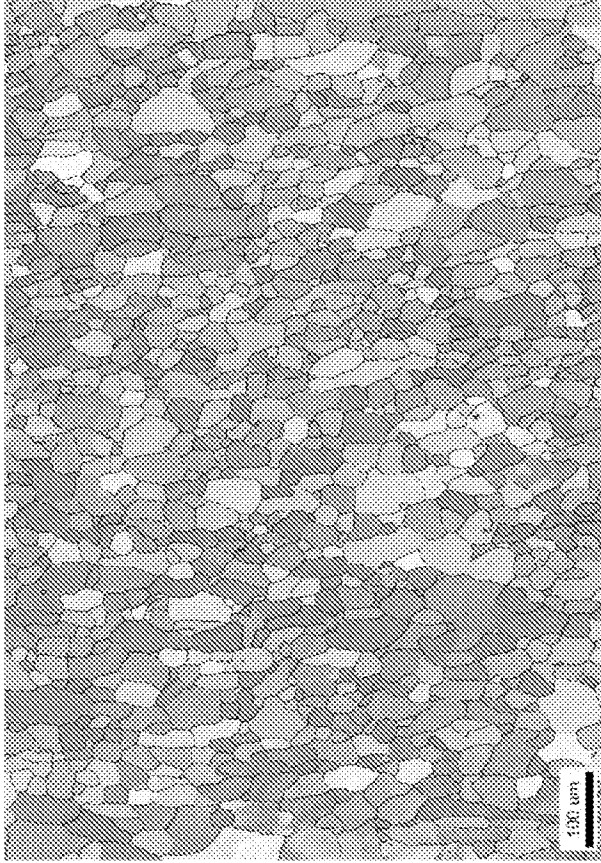


FIG. 4: Alloy A1-22

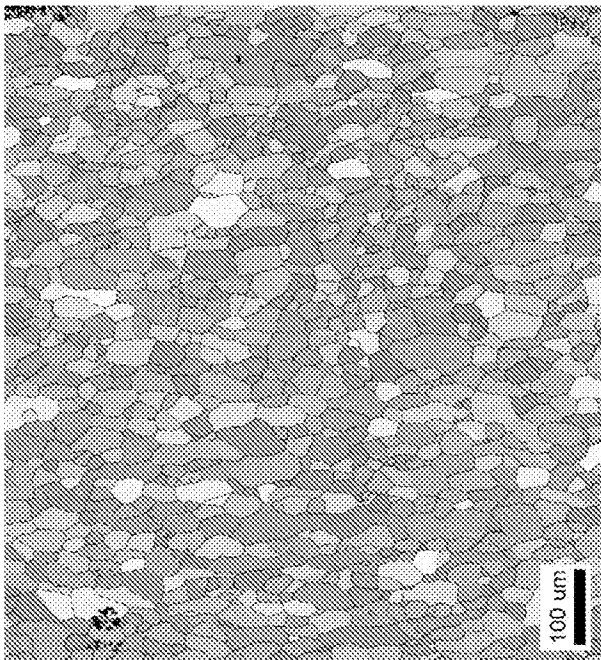


FIG. 3: Alloy A1-19

FIG. 5 - Strength v. n Value

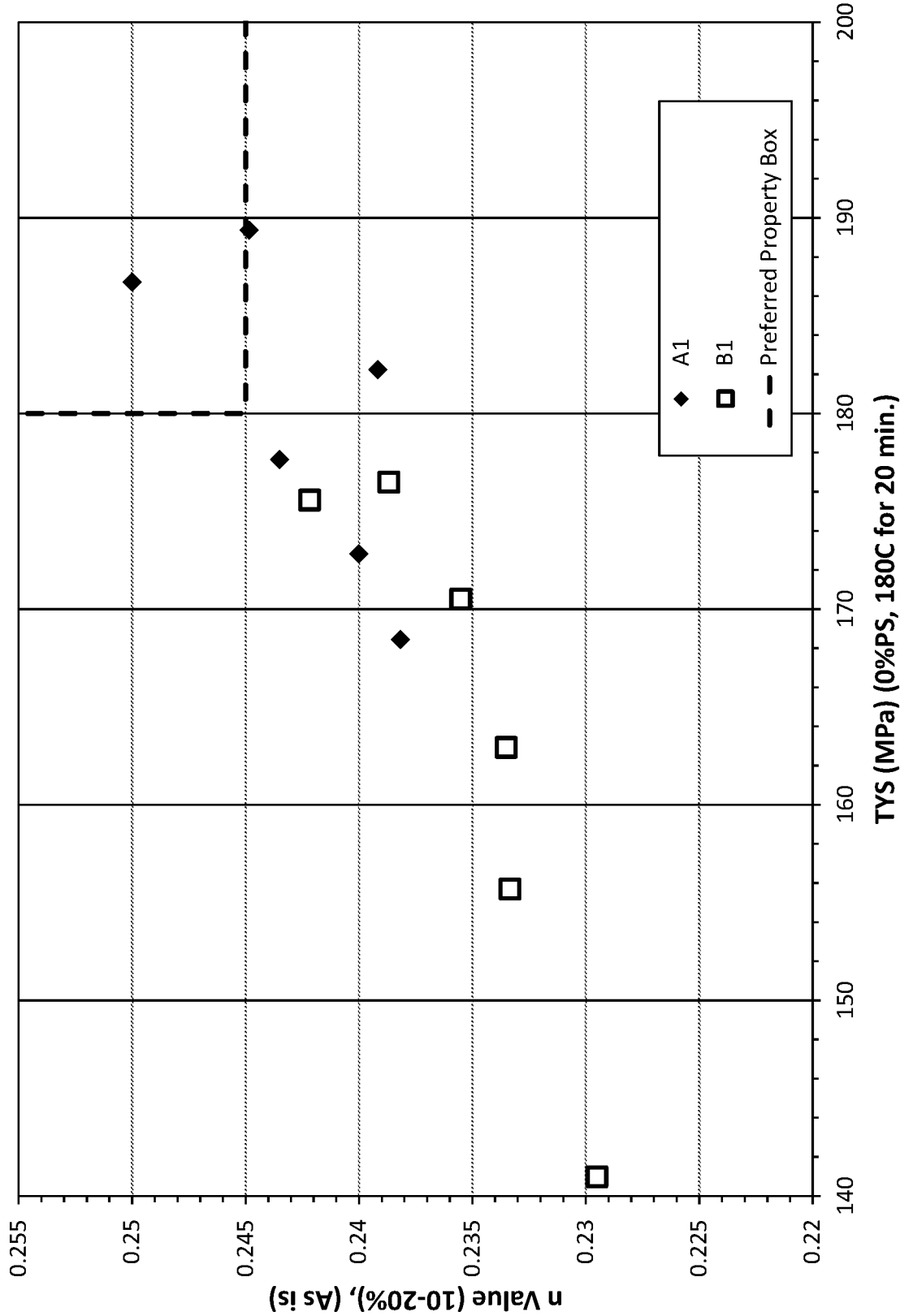


FIG. 6 - Strength v. Uniform Elongation

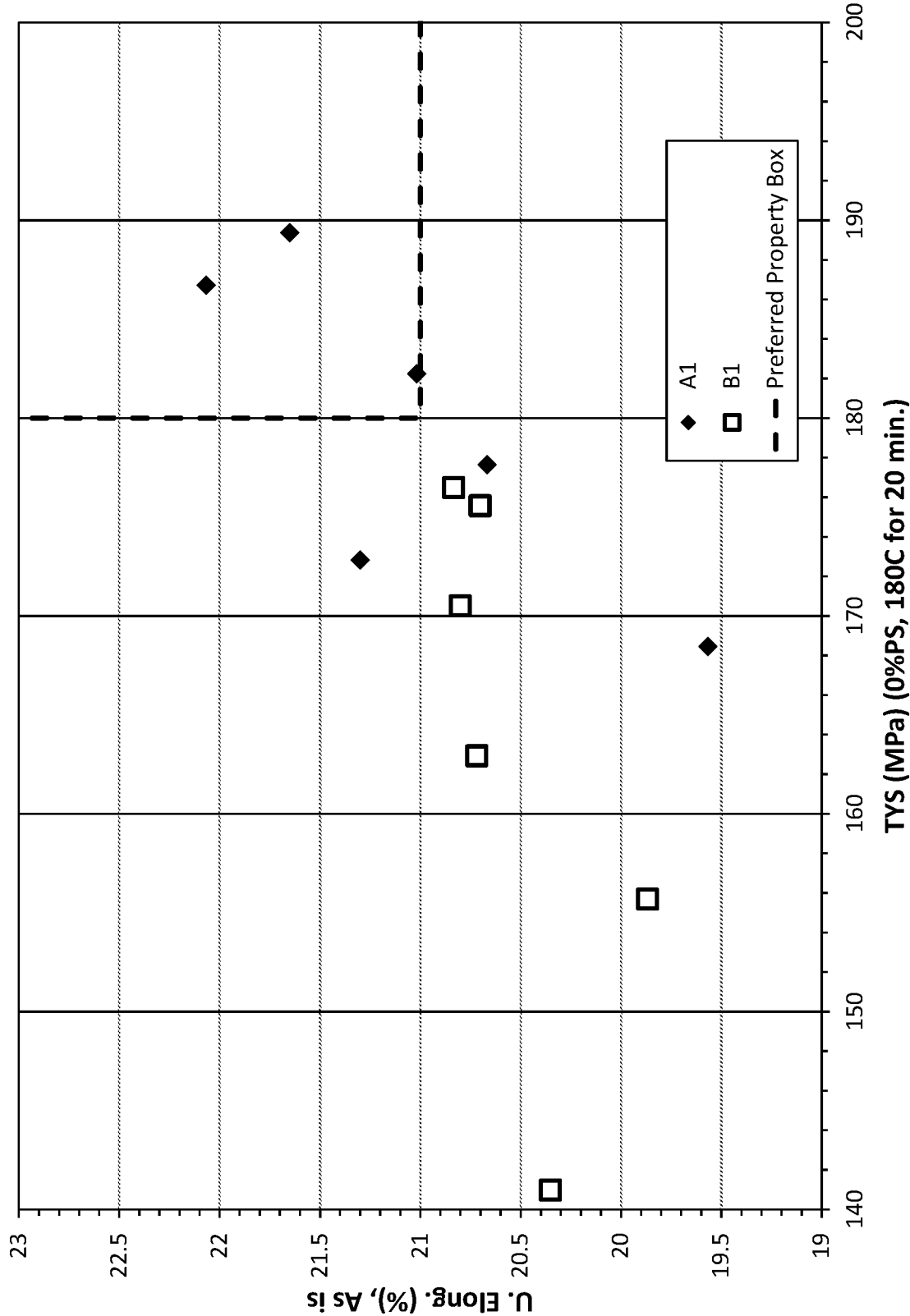


FIG. 7 - Strength v. n Value

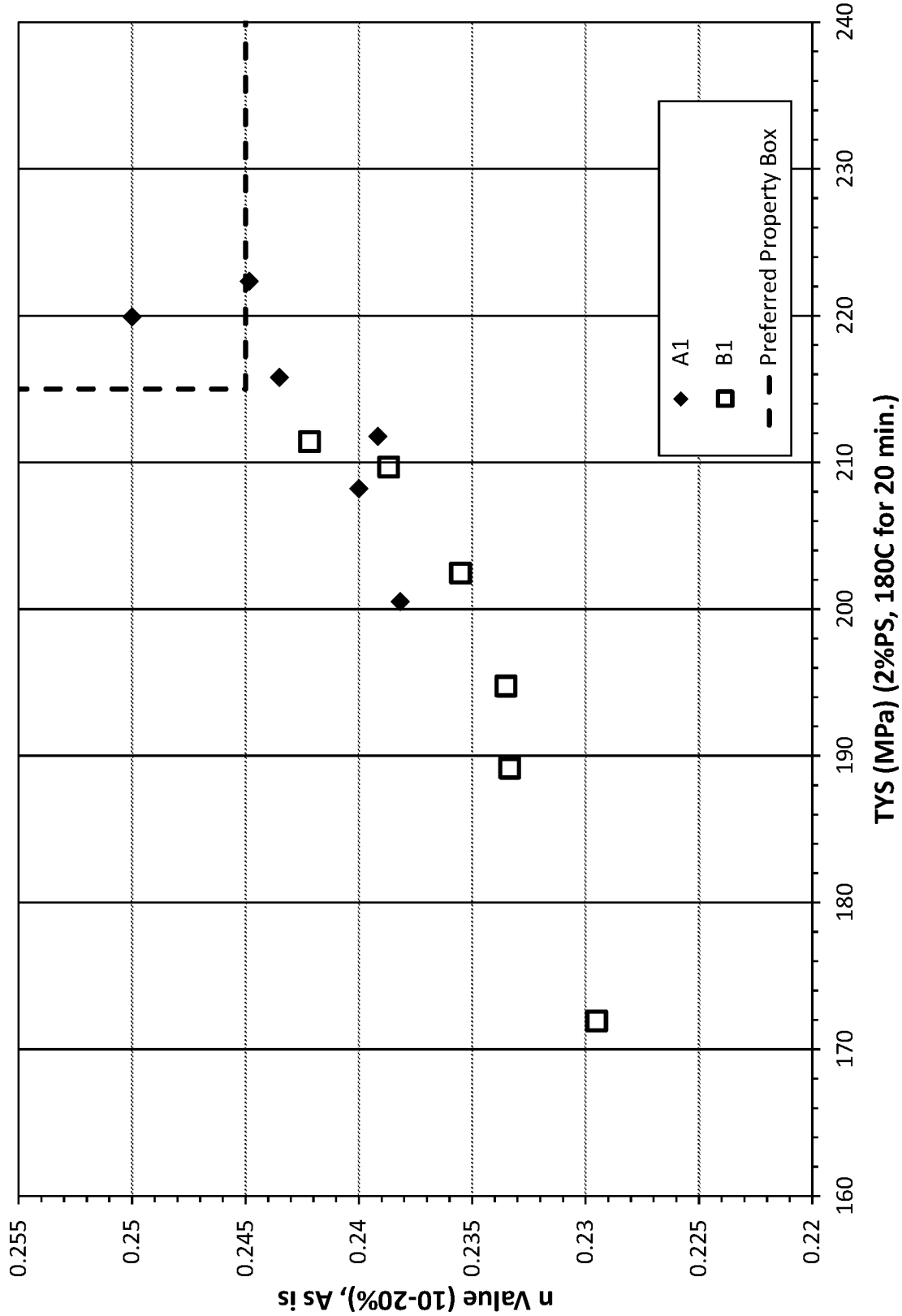
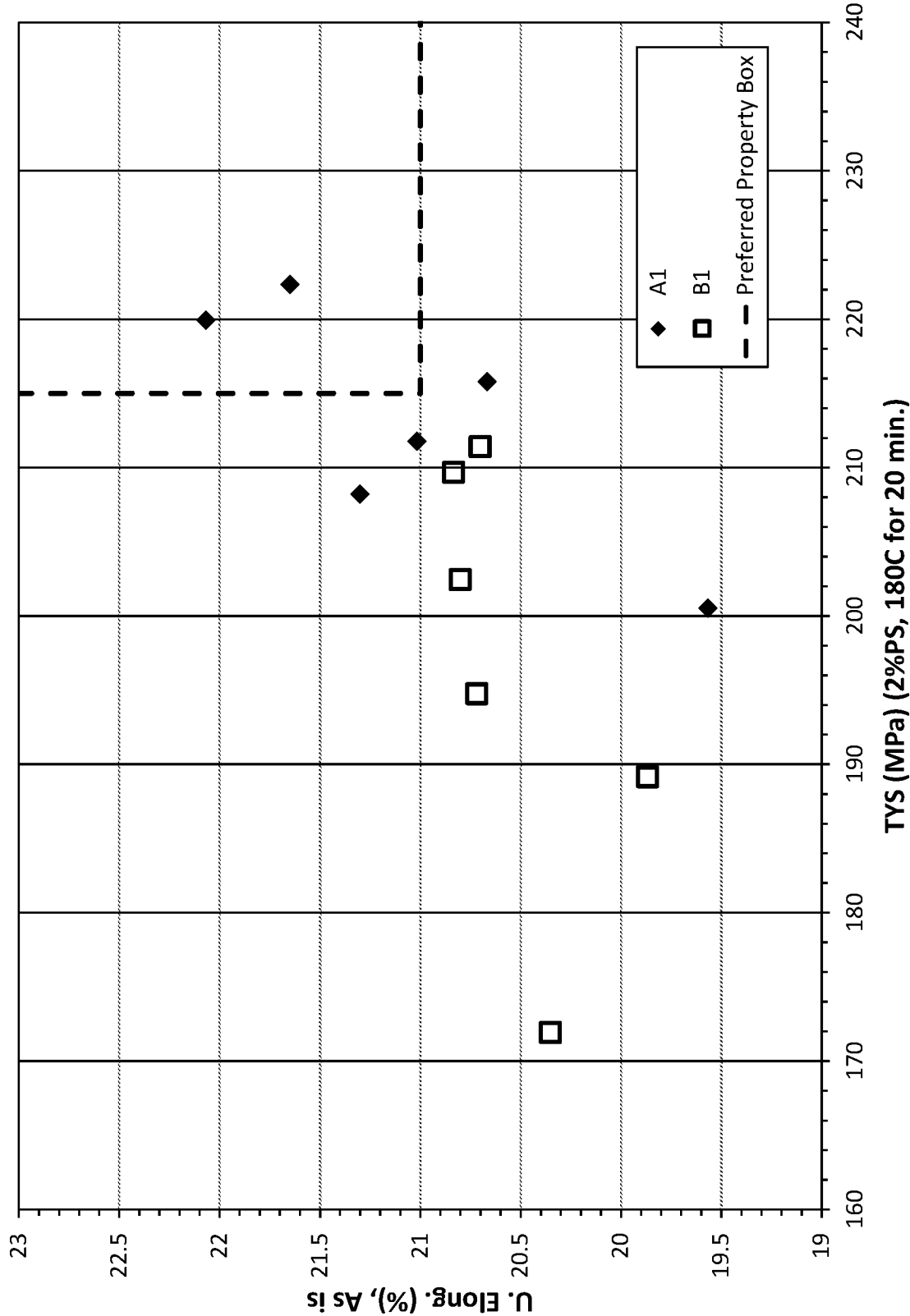


FIG. 8 - Strength v. Uniform Elongation



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2019/064148**A. CLASSIFICATION OF SUBJECT MATTER****C22C 21/02(2006.01)i, C22F 1/043(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C22C 21/02; C22C 21/00; C22C 21/06; C22C 21/08; C22C 21/14; C22F 001/04; C22F 1/057; C22F 1/043

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: 6xxx aluminum alloy, silicon, magnesium, hot rolling, cold rolling, annealing, solution heat treating, aging

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2009-041045 A (NIPPON STEEL CORP et al.) 26 February 2009 paragraph [0002], claim 1, and table 1	1-22
Y		23-32
Y	WO 2015-112450 A1 (ALCOA INC.) 30 July 2015 paragraphs [0019]-[0025] and claims 21-22	23-32
A	CN 105441740 A (SUZHOU INSTITUTE FOR NONFERROUS METALS RESEARCH CO., LTD. et al.) 30 March 2016 paragraph [0006] and claims 1-2	1-32
A	US 2004-0129353 A1 (VERMA et al.) 08 July 2004 claim 10	1-32
A	US 2017-0175240 A1 (NOVELIS INC.) 22 June 2017 claim 1	1-32



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

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Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea



Facsimile No. +82-42-481-8578

Authorized officer

LEE, Hun Gil

Telephone No. +82-42-481-8525



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2019/064148

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