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(54) **5XXX-LITHIUM ALUMINUM ALLOYS, AND METHODS FOR PRODUCING THE SAME**

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USPC **420/532**; 420/541

(57) **ABSTRACT**

New 5xxx-lithium aluminum alloys and related products are disclosed. The new 5xxx-lithium aluminum alloy may contain from 3.75 to 5.0 wt. % Mg, from 1.6 to 2.3 wt. % Li, and from 0.50 to 2.5 wt. % Zn, among others.

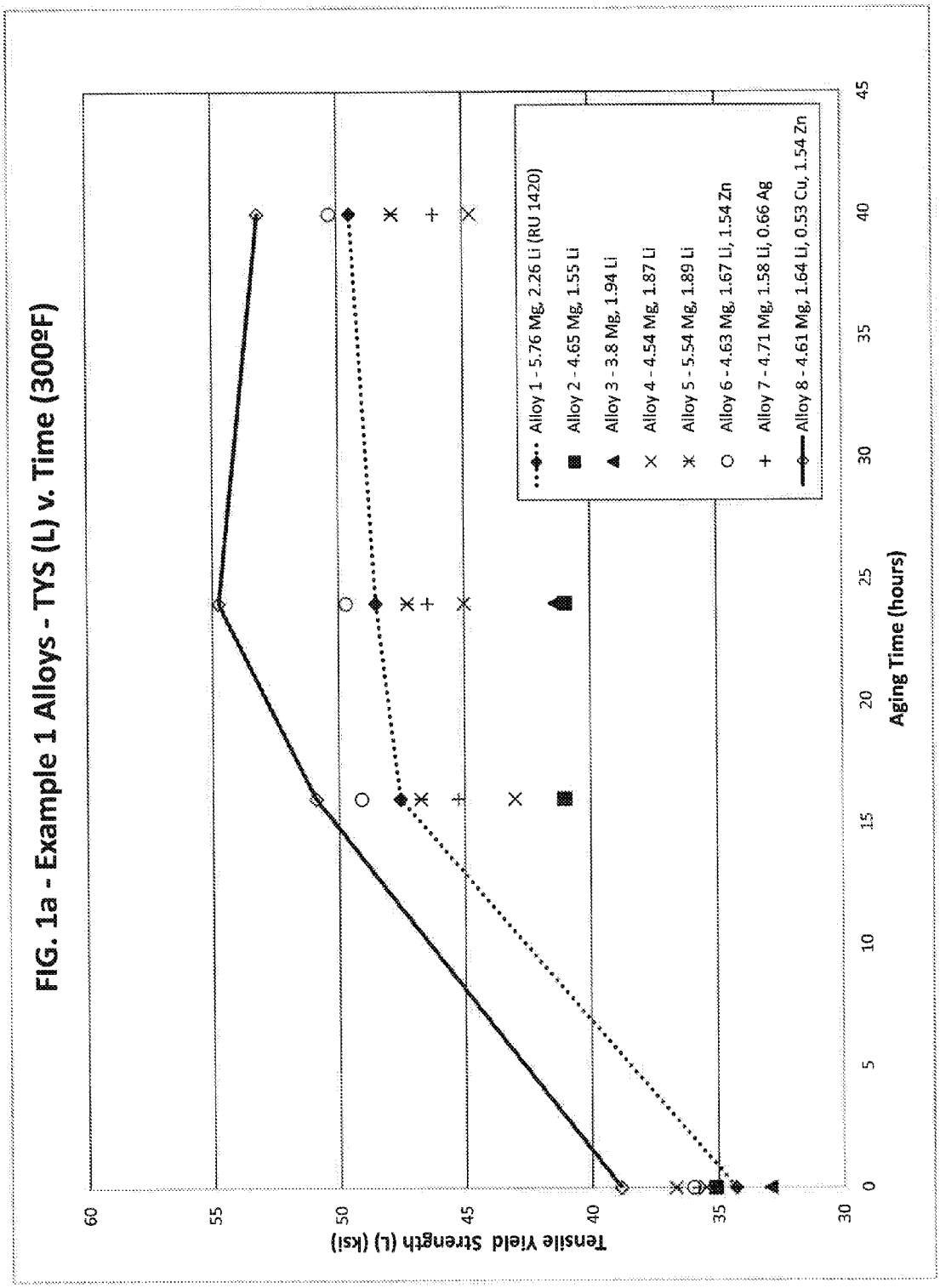
FIG. 1a - Example 1 Alloys - TYS (L) v. Time (300ºF)
Tensile Yield Strength (L) (ksi)
Aging Time (hours)
60
55
50
45
40
35
30
0
5
10
15
20
25
30
35
40
45
Alloy 1 - 5.76 Mg, 2.26 Li (RU 1420)
Alloy 2 - 4.65 Mg, 1.55 Li
Alloy 3 - 3.8 Mg, 1.94 Li
Alloy 4 - 4.54 Mg, 1.87 Li
Alloy 5 - 5.54 Mg, 1.89 Li
Alloy 6 - 4.63 Mg, 1.67 Li, 1.54 Zn
Alloy 7 - 4.71 Mg, 1.58 Li, 0.66 Ag
Alloy 8 - 4.61 Mg, 1.64 Li, 0.53 Cu, 1.54 Zn

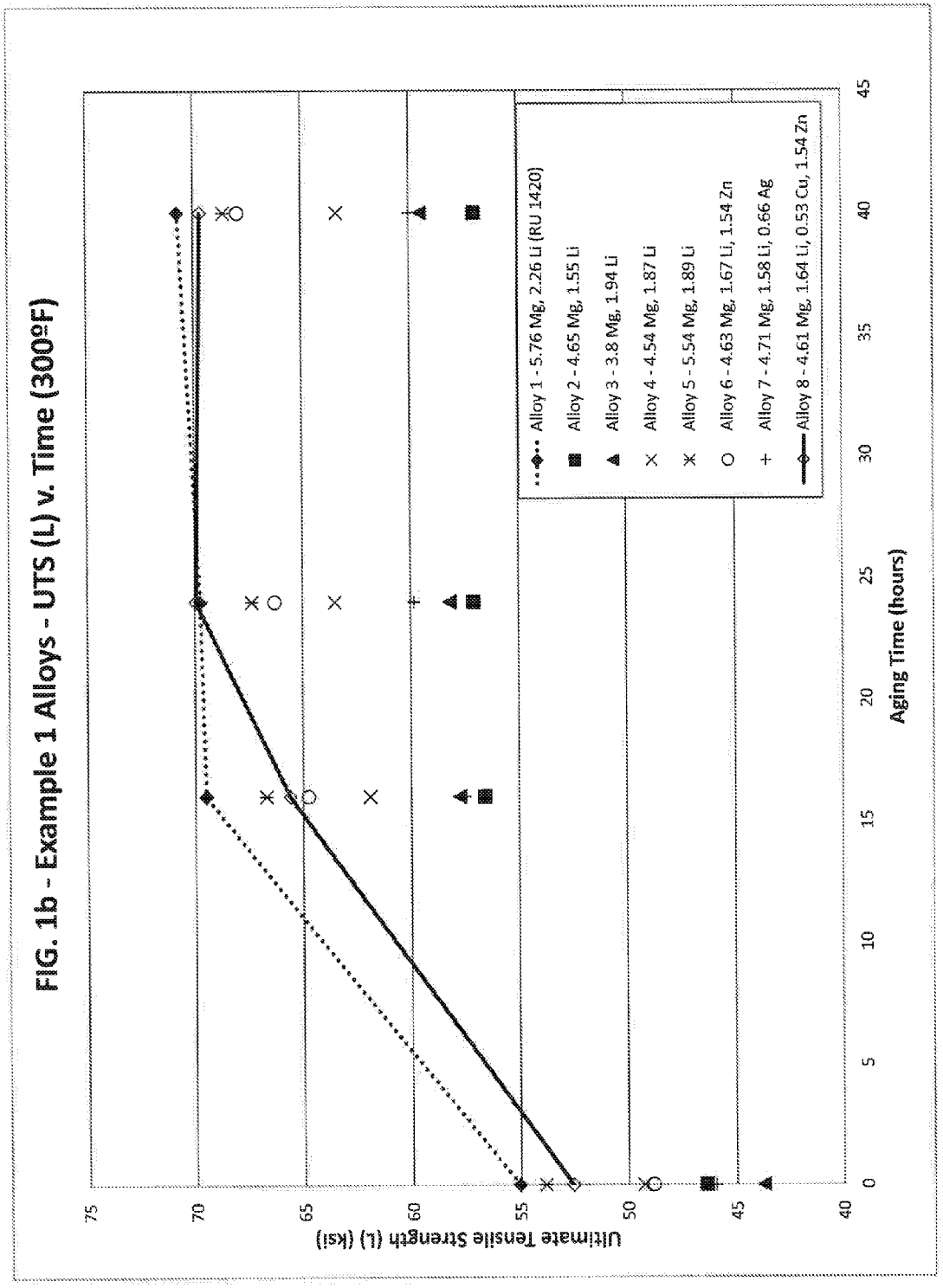
FIG. 1b - Example 1 Alloys - UTS (L) v. Time (300ºF)
Ultimate Tensile Strength (L) (ksi)
Aging Time (hours)
75
70
65
60
55
50
45
40
0
5
10
15
20
25
30
35
40
45
Alloy 1 - 5.76 Mg, 2.26 Li (RU 1420)
Alloy 2 - 4.65 Mg, 1.55 Li
Alloy 3 - 3.8 Mg, 1.94 Li
Alloy 4 - 4.54 Mg, 1.87 Li
Alloy 5 - 5.54 Mg, 1.89 Li
Alloy 6 - 4.63 Mg, 1.67 Li, 1.54 Zn
Alloy 7 - 4.71 Mg, 1.58 Li, 0.66 Ag
Alloy 8 - 4.61 Mg, 1.64 Li, 0.53 Cu, 1.54 Zn

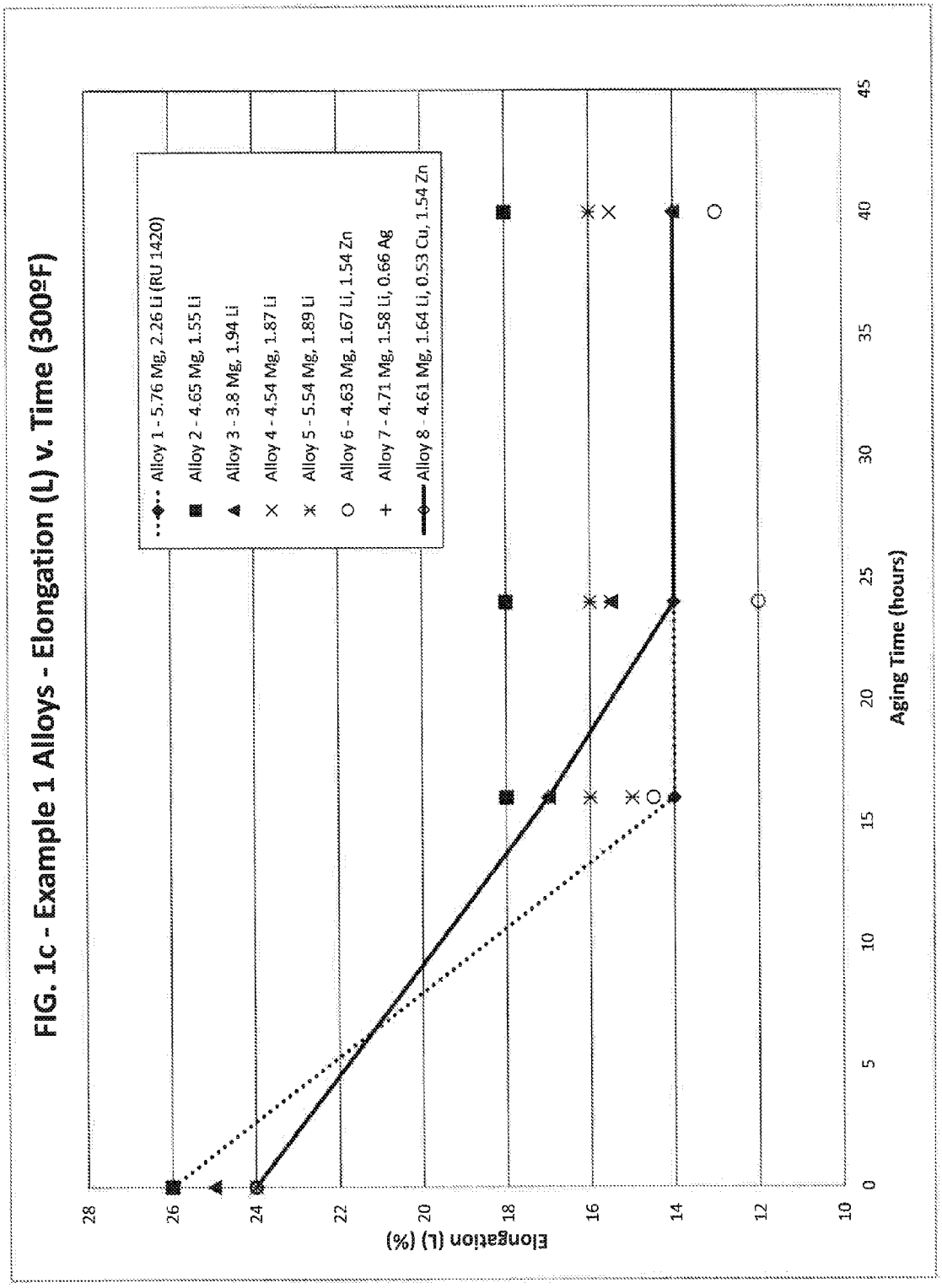
FIG. 1c - Example 1 Alloys - Elongation (L) v. Time (300ºF)
Elongation (L) (%)
Aging Time (hours)
Alloy 1 - 5.76 Mg, 2.26 Li (RU 1420)
Alloy 2 - 4.65 Mg, 1.55 Li
Alloy 3 - 3.8 Mg, 1.94 Li
Alloy 4 - 4.54 Mg, 1.87 Li
Alloy 5 - 5.54 Mg, 1.89 Li
Alloy 6 - 4.63 Mg, 1.67 Li, 1.54 Zn
Alloy 7 - 4.71 Mg, 1.58 Li, 0.66 Ag
Alloy 8 - 4.61 Mg, 1.64 Li, 0.53 Cu, 1.54 Zn
28
26
24
22
20
18
16
14
12
10
0
5
10
15
20
25
30
35
40
45

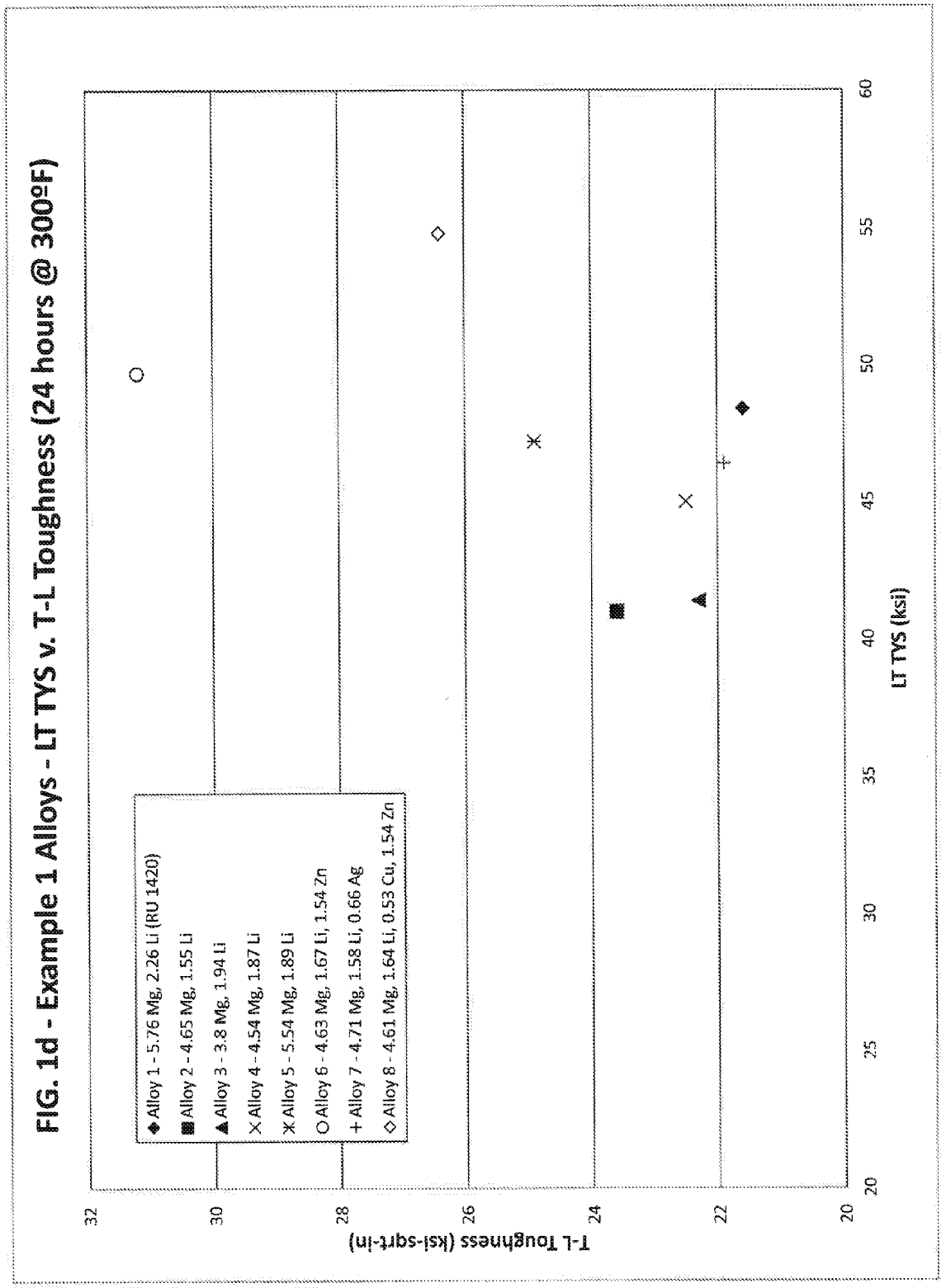
FIG. 1d - Example 1 Alloys - LT TYS v. T-L Toughness (24 hours @ 300ºF)
◆ Alloy 1 - 5.76 Mg, 2.26 Li (RU 1420)
■ Alloy 2 - 4.65 Mg, 1.55 Li
▲ Alloy 3 - 3.8 Mg, 1.94 Li
× Alloy 4 - 4.54 Mg, 1.87 Li
✳ Alloy 5 - 5.54 Mg, 1.89 Li
○ Alloy 6 - 4.63 Mg, 1.67 Li, 1.54 Zn
+ Alloy 7 - 4.71 Mg, 1.58 Li, 0.66 Ag
◇ Alloy 8 - 4.61 Mg, 1.64 Li, 0.53 Cu, 1.54 Zn
T-L Toughness (ksi-sqrt-in)
32
30
28
26
24
22
20
20
25
30
35
40
45
50
55
60
LT TYS (ksi)

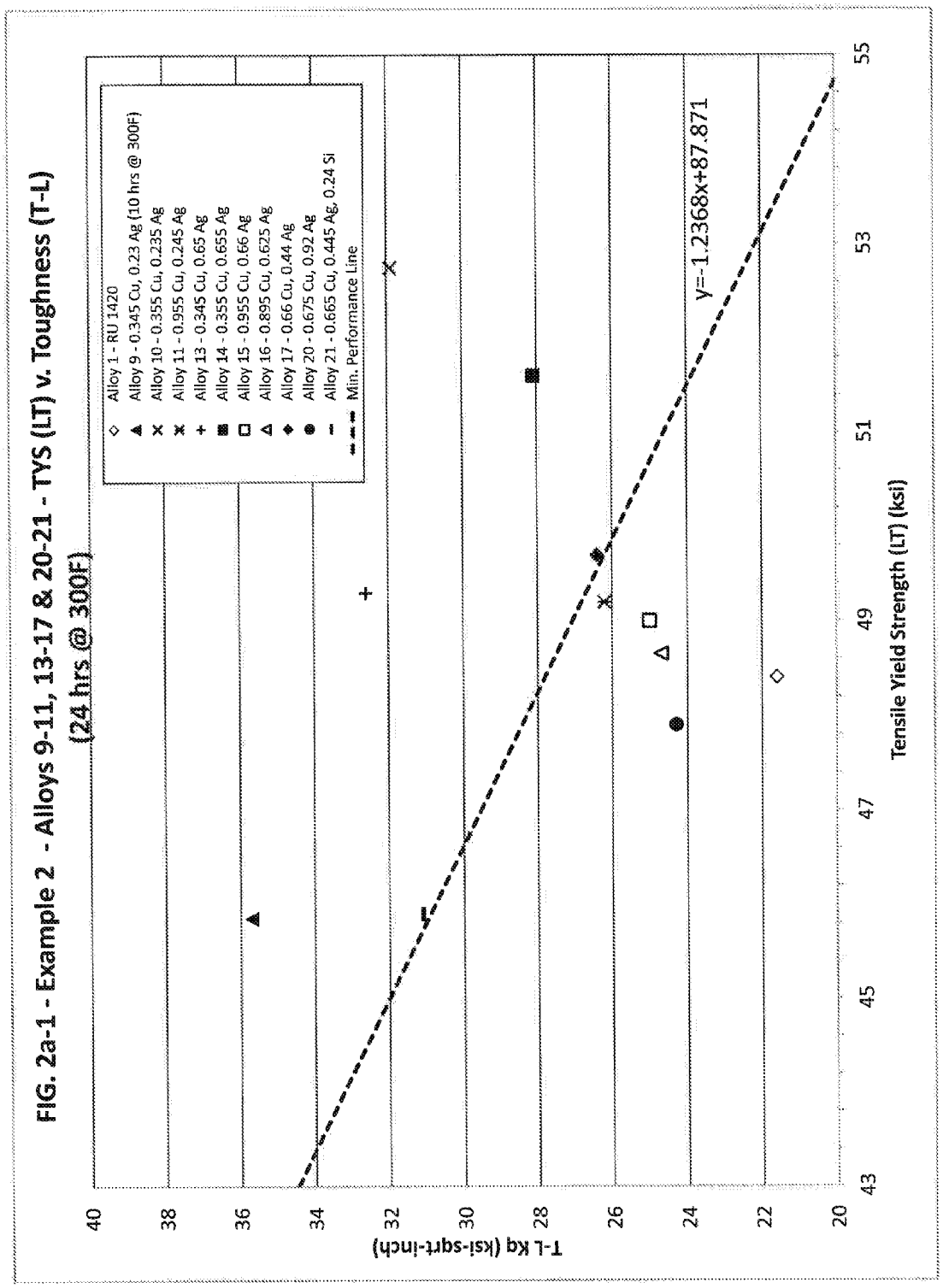
FIG. 2a-1 - Example 2 - Alloys 9-11, 13-17 & 20-21 - TYS (LT) v. Toughness (T-L)
(24 hrs @ 300F)
Alloy 1 - RU 1420
Alloy 9 - 0.345 Cu, 0.23 Ag (10 hrs @ 300F)
Alloy 10 - 0.355 Cu, 0.235 Ag
Alloy 11 - 0.955 Cu, 0.245 Ag
Alloy 13 - 0.345 Cu, 0.65 Ag
Alloy 14 - 0.355 Cu, 0.655 Ag
Alloy 15 - 0.955 Cu, 0.66 Ag
Alloy 16 - 0.895 Cu, 0.625 Ag
Alloy 17 - 0.66 Cu, 0.44 Ag
Alloy 20 - 0.675 Cu, 0.92 Ag
Alloy 21 - 0.665 Cu, 0.445 Ag, 0.24 Si
Min. Performance Line
y=-1.2368x+87.871
T-L Kq (ksi-sqrt-inch)
Tensile Yield Strength (LT) (ksi)
40
38
36
34
32
30
28
26
24
22
20
43
45
47
49
51
53
55

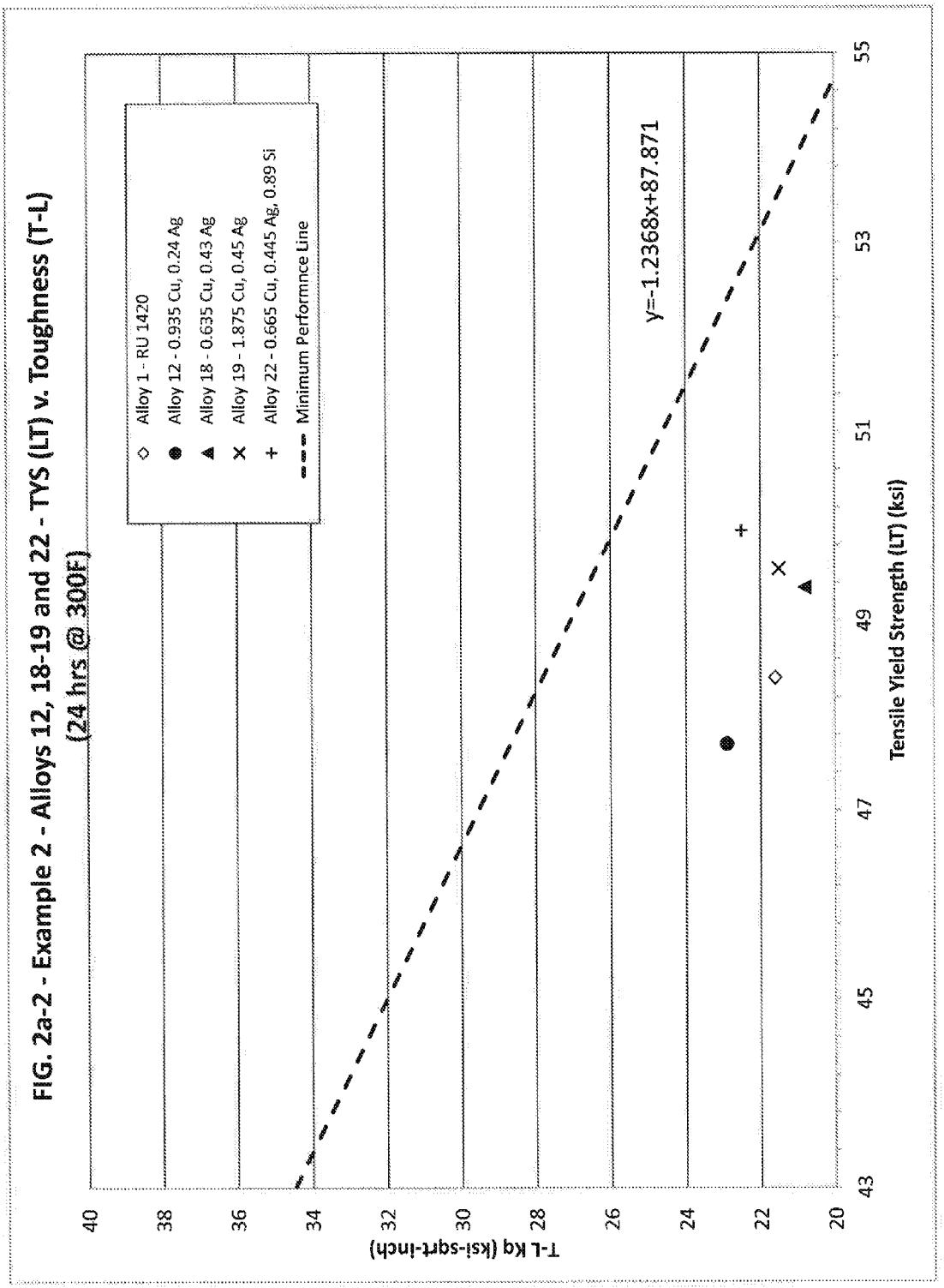
FIG. 2a-2 - Example 2 - Alloys 12, 18-19 and 22 - TYS (LT) v. Toughness (T-L)
(24 hrs @ 300F)
Alloy 1 - RU 1420
Alloy 12 - 0.935 Cu, 0.24 Ag
Alloy 18 - 0.635 Cu, 0.43 Ag
Alloy 19 - 1.875 Cu, 0.45 Ag
Alloy 22 - 0.665 Cu, 0.445 Ag, 0.89 Si
Minimum Performnce Line
y=-1.2368x+87.871
T-L Kq (ksi-sqrt-inch)
Tensile Yield Strength (LT) (ksi)
40
38
36
34
32
30
28
26
24
22
20
43
45
47
49
51
53
55

5XXX-LITHIUM ALUMINUM ALLOYS, AND METHODS FOR PRODUCING THE SAME

BACKGROUND

[0001] Aluminum alloys are useful in a variety of applications. However, improving one property of an aluminum alloy without degrading another property often proves elusive.

SUMMARY OF THE DISCLOSURE

[0002] Broadly, the present disclosure relates to new 5xxx-lithium aluminum alloy products having an improved combination of properties. The new 5xxx-lithium aluminum alloy products are made from aluminum alloys containing from 3.75 to 5.0 wt. % magnesium (Mg), from 1.6 to 2.3 wt. % lithium (Li), from 0.50 to 2.5 wt. % zinc (Zn), 0.05 to 0.50 wt. % of a grain structure control element selected from the group consisting of Zr, Sc, Cr, V, Hf, other rare earth elements, and combinations thereof, optionally up to 1.0 wt. % copper (Cu), optionally up to 1.0 wt. % silver (Ag), wherein wt. % Cu+wt. % Ag≤1.15 wt. %, wherein, when the aluminum alloy contains not greater than 0.04 wt. % Cu and not greater than 0.04 wt. % Ag, the aluminum alloy contains at least 0.75 wt. % zinc, optionally up to 0.5 wt. % silicon (Si), optionally up to 1.0 wt. % manganese (Mn), optionally up to 0.25 wt. % Fe, optionally up to 0.15 wt. % Ti, the balance being aluminum, other elements and impurities, wherein the aluminum alloy contains not greater than 0.10 wt. % of any one of the other elements, and wherein the aluminum alloy contains not greater than 0.35 wt. % total of the other elements. The new 5xxx-lithium aluminum alloys may realize an improved combination of properties, such as an improved combination of two or more of strength, fracture toughness, density, fatigue crack growth, and/or corrosion resistance, among others. The new 5xxx-lithiurn aluminum alloys may be used in aerospace and defense applications, among others.

[0003] 5xxx aluminum alloys are aluminum alloys having magnesium as the predominate alloying element other than aluminum. The new 5xxx-lithium aluminum alloys of the present patent application are 5xxx aluminum alloys having 3.75 to 5.0 wt. % Mg, from 1.6-2.3 wt. % Li, and from 0.5 to 2.5 wt. % Zn, among others, as described below. The new 5xxx-lithium aluminum alloy products are generally in the form of wrought products, and may be produced by casting the new 5xxx-lithium alloy, after which it is homogenized, then hot worked to an intermediate gauge or a final gauge, then optionally cold worked, then solution heat treated and quenched, then optionally cold worked, and then optionally artificially aged. Thus, the new 5xxx-lithium aluminum alloy products are generally in the T3 or T8 temper, such tempers being known to those skilled in the art and defined by the Aluminum Association. The above hot working step may be completed by rolling, extruding, or forging to produce a sheet or plate, an extrusion, or a forging, respectively.

[0004] The new 5xxx-lithium aluminum alloy products generally contain from 3.75 to 5.0 wt. % Mg. In one embodiment, a new 5xxx-lithium aluminum alloy product contains at least 4.0 wt. % Mg. In another embodiment, a new 5xxx-lithium aluminum alloy product contains at least 4.1 wt. % Mg. In yet another embodiment, a new 5xxx-lithium aluminum alloy product contains at least 4.2 wt. % Mg. In another embodiment, a new 5xxx-lithium aluminum alloy product contains at least 4.3 wt. % Mg. In one embodiment, a new 5xxx-lithium aluminum alloy product contains not greater than 4.9 wt. % Mg. In another embodiment, a new 5xxx-lithium aluminum alloy product contains not greater than 4.8 wt. % Mg. In yet another embodiment, a new 5xxx-lithium aluminum alloy product contains not greater than 4.7 wt. % Mg. In another embodiment, a new 5xxx-lithium aluminum alloy product contains not greater than 4.6 wt. % Mg.

[0005] The new 5xxx-lithium aluminum alloy products generally contain from 1.60 to 2.30 wt. % Li. In one embodiment, a new 5xxx-lithium aluminum alloy product contains at least 1.65 wt. % Li. In another embodiment, a new 5xxx-lithium aluminum alloy product contains at least 1.70 wt. % Li. In yet another embodiment, a new 5xxx-lithium aluminum alloy product contains at least 1.75 wt. % Li. In one embodiment, a new 5xxx-lithium aluminum alloy product contains not greater than 2.20 wt. % Li. In another embodiment, a new 5xxx-lithium aluminum alloy product contains not greater than 2.10 wt. % Li.

[0006] The new 5xxx-lithium aluminum alloy products generally contain from 0.5 to 2.50 wt. % Zn. In one embodiment, a new 5xxx-lithium aluminum alloy product contains at least 0.60 wt. % Zn. In another embodiment, a new 5xxx-lithium aluminum alloy product contains at least 0.70 wt. % Zn. In yet another embodiment, a new 5xxx-lithium aluminum alloy product contains at least 0.80 wt. % Zn. In another embodiment, a new 5xxx-lithium aluminum alloy product contains at least 0.90 wt. % Zn. In yet another embodiment, a new 5xxx-lithium aluminum alloy product contains at least 1.00 wt. % Zn. In one embodiment, a new 5xxx-lithium aluminum alloy product contains not greater than 2.25 wt. % Zn. In another embodiment, a new 5xxx-lithium aluminum alloy product contains not greater than 2.00 wt. % Zn.

[0007] The new 5xxx-lithium aluminum alloy products may optionally contain up to 1.0 wt. % copper (Cu). In embodiments where copper is used, the new 5xxx-lithium aluminum alloy products contain at least 0.05 wt. % Cu. In one embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.15 wt. % Cu. In another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.25 wt. % Cu. In yet another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.30 wt. % Cu. In one embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.90 wt. % Cu. In another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.80 wt. % Cu. In yet another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.70 wt. % Cu. In another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.60 wt. % Cu. In some embodiments copper is present as an impurity, and in these embodiments the new 5xxx-lithium aluminum alloy products contain not greater than 0.04 wt. % Cu.

[0008] The new 5xxx-lithium aluminum alloy products may optionally contain up to 1.0 wt. % silver (Ag). In embodiments where silver is used, the new 5xxx-lithium aluminum alloy products contain at least 0.05 wt. % Ag. In one embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.15 wt. % Ag. In another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.25 wt. % Ag. In yet another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.30 wt. % Ag. In one embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.90 wt. % Ag. In another embodiment, the new 5xxx-lithium aluminum alloy products

contain not greater than 0.80 wt. % Ag. In yet another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.70 wt. % Ag. In another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.60 wt. % Ag. In some embodiments silver is present as an impurity, and in these embodiments the new 5xxx-lithium aluminum alloy products contain not greater than 0.04 wt. % Ag.

[0009] When the new 5xxx-lithium aluminum alloy products contain copper and silver, the new 5xxx-lithium aluminum alloy products contain not greater than 1.15 wt. %. Cu+Ag (i.e., (wt % Cu)+(wt. % Ag)≤1.15 wt. %). In one embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 1.10 wt. % Cu+Ag. In another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 1.05 wt. % In another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 1.00 wt. % Cu+Ag.

[0010] In embodiments where copper and/or or silver are used, the new 5xxx-lithium aluminum alloy products generally contain at least 0.15 wt. % Cu+Ag (i.e., (wt. % Cu)+(wt. % Ag)≥0.15 wt. %), where at least one of copper and silver is present. In one embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.25 wt. % Cu+Ag. In another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.35 wt. % Cu+Ag. In yet another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.40 wt. % Cu+Ag. In another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.45 wt. % Cu+Ag. In yet another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.50 wt. % Cu+Ag.

[0011] When copper and/or silver are used, the alloys may include less zinc. For example, when the alloys include at least 0.05 wt. % Cu or at least 0.05 wt. % Ag, the alloys may include as low as 0.50 wt. % zinc. When copper and/or silver is not used, the alloys require higher zinc. For example, when the alloys include not greater than 0.04 wt. % Cu (i.e., Cu as an impurity) and not greater than 0.04 wt. % Ag (i.e., Ag as an impurity), the alloys include at least 0.75 wt. % zinc.

[0012] The new 5xxx-lithium aluminum alloy products may optionally contain up to 0.5 wt. % silicon (Si). In embodiments where silicon is used, the new 5xxx-lithium aluminum alloy products contain at least 0.05 wt. % Si. In one embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.35 wt. % Si. In another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.25 wt. % Si. In some embodiments silicon is present as an impurity, and in these embodiments the new 5xxx-lithium aluminum alloy products contain not greater than 0.04 wt. % Si.

[0013] The new 5xxx-lithium aluminum alloy products may optionally contain up to 1.0 wt. % manganese (Mn), In embodiments where manganese is used, the new 5xxx-lithium aluminum alloy products contain at least 0.05 wt. % Mn. In one embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.20 wt. % Mn. In another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.30 wt. % Mn. In yet another embodiment, the new 5xxx-lithium aluminum alloy products contain at least 0.40 wt. % Mn. In one embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.75 wt. % Mn. In another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.50 wt. % Mn. In some embodiments manganese is present as an impurity, and in these embodiments the new 5xxx-lithium aluminum alloy products contain not greater than 0.04 wt. % Mn.

[0014] The new 5xxx-lithium aluminum alloy products may include 0.05 to 0.50 wt. % of at least one grain structure control element selected from the group consisting of zirconium (Zr), scandium (Sc), chromium (Cr), vanadium (V) and/or hafnium (HO, and/or other rare earth elements, and such that the utilized grain structure control element(s) is/are maintained below maximum solubility. As used herein, "grain structure control element" means elements or compounds that are deliberate alloying additions with the goal of forming second phase particles, usually in the solid state, to control solid state grain structure changes during thermal processes, such as recovery and recrystallization. For purposes of the present patent application, grain structure control elements include Zr, Sc, Cr, V, Hf, other rare earth elements, and combinations thereof, but excludes Mn.

[0015] The amount of grain structure control material utilized in an alloy is generally dependent on the type of material utilized for grain structure control and/or the alloy production process. In one embodiment, the grain structure control element is Zr, and the alloy includes from 0.05 wt. % to 0.20 wt. % Zr. In another embodiment, the alloy includes from 0.05 wt. % to 0.15 wt. % Zr. In another embodiment, the alloy includes 0.07 to 0.14 wt. % Zr. In another embodiment, the alloy includes 0.08-0.13 wt. % Zr. In one embodiment, the aluminum alloy includes at least 0.07 wt. % Zr. In another embodiment, the aluminum alloy includes at least 0.08 wt. % Zr. In one embodiment, the aluminum alloy includes not greater than 0.18 wt. % Zr. In another embodiment, the aluminum alloy includes not greater than 0.15 wt. % Zr. In another embodiment, the aluminum alloy includes not greater than 0.14 wt. % Zr. In another embodiment, the aluminum alloy includes not greater than 0.13 wt. % Zr.

[0016] The new 5xxx-lithium aluminum alloy products may include up to 0.15 wt. % Ti cumulatively for ingot grain refining and/or other purposes. Grain refiners are inoculants or nuclei to seed new grains during solidification of the alloy. An example of a grain refiner is a 9.525 mm rod comprising 96% aluminum, 3% titanium (Ti) and 1% boron (B), where virtually all boron is present as finely dispersed TiB_2 particles. During casting, the grain refining rod is fed in-line into the molten alloy flowing into the casting pit at a controlled rate. The amount of grain refiner included in the alloy is generally dependent on the type of material utilized for grain refining and the alloy production process. Examples of grain refiners include Ti combined with B (e.g., TiB_2) or carbon (TiC), although other grain refiners, such as Al—Ti master alloys may be utilized. Generally, grain refiners are added in an amount ranging from 0.0003 wt. % to 0.005 wt % to the alloy, depending on the desired as-cast grain size. In addition, Ti may be separately added to the alloy in an amount up to 0.15 wt. % (cumulative), depending on product form, to increase the effectiveness of grain refiner, and typically in the range of 0.01 to 0.03 wt. % Ti. When Ti is included in the alloy, it is generally present in an amount of from 0.01 to 0.10 wt. %. In one embodiment, the aluminum alloy includes a grain refiner, and the grain refiner is at least one of TiB_2 and TiC, where the wt. % of Ti in the alloy is from 0.01 to 0.06 wt. %, or from 0.01 to 0.03 wt. %.

[0017] The new 5xxx-lithium aluminum alloy products may include impurities of iron, copper, silver, silicon and/or manganese. Iron may be included in the alloy as an impurity

in an amount of up to 0.25 wt. %. In one embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.15 wt. % Fe as an impurity. In another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.12 wt. % Fe as an impurity. In yet another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.10 wt. % Fe as an impurity. In another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.08 wt. % Fe as an impurity. In yet another embodiment, the new 5xxx-lithium aluminum alloy products contain not greater than 0.06 wt. % Fe as an impurity. As described above, copper, silver, silicon and/or manganese may be included in the alloy as an impurity, and when any of such elements are in the alloy as an impurity, the new 5xxx-lithium aluminum alloy products may include up to 0.04 wt. % each of any of such elements.

[0018] The new 5xxx-lithium aluminum alloy products generally contain low amounts of "other elements" (e.g., casting aids). As used herein, "other elements" means any other element of the periodic table except for aluminum and the above-described magnesium, lithium, zinc, copper, silver, silicon, manganese, titanium, grain structure control elements (i.e., Zr, Sc, Cr, V Hf, and other rare earth elements), and iron, as described above. In one embodiment, a new 5xxx-lithium aluminum alloy product contains not more than 0.10 wt. % each of any other element, with the total combined amount of these other elements not exceeding 0.35 wt. %. In another embodiment, each one of these other elements, individually, does not exceed 0.05 wt. % in a new 5xxx-lithium aluminum alloy product, and the total combined amount of these other elements does not exceed 0.15 wt. % in a 5xxx-lithium aluminum alloy product. In another embodiment, each one of these other elements, individually, does not exceed 0.03 wt. % in a 5xxx-lithium aluminum alloy product, and the total combined amount of these other elements does not exceed 0.10 wt. % in a 5xxx-lithium aluminum alloy product.

[0019] For the purposes of this patent application, the below chart identifies the difference between impurities and other elements.

Impurities	Other Elements
Iron (when the alloy contains 0.25 wt. % Fe or less)	Any element of the periodic table except the following:
Optionally copper (when the alloy contains 0.04 wt. % Cu or less)	Aluminum
	Magnesium
	Lithium
Optionally silver (when the alloy contains 0.04 wt. % Ag or less)	Zinc
	Copper
	Silver
Optionally silicon (when the alloy contains 0.04 wt. % Si or less)	Silicon
	Titanium
Optionally manganese (when the alloy contains 0.04 wt. % Mn or less)	Manganese
	Zirconium
	Scandium
	Chromium
	Vanadium
	Hafnium
	Other rare earth elements (i.e., Yttrium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Terbium, Dysprosium, Holmium, Erbium, Thulium, Ytterbium and Lutetium)

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] FIGS. **1***a*-**1***d* are graphs illustrating mechanical properties of various Example 1 alloys.

[0021] FIG. **2***a*-**1** is a graph illustrating the strength-toughness performance of various Example 2 alloys.

[0022] FIG. **2***a*-**2** is a graph illustrating the strength-toughness performance of various Example 2 alloys.

DETAILED DESCRIPTION

EXAMPLE 1

[0023] Various 5xxx-lithium aluminum alloys were cast in book molds to make ingots approximately 3 inches thick. The alloy compositions are provided in Table 1, below.

TABLE 1

Example 1 Alloy Compositions and Density
(all values in weight percent)

Alloy	Mg	Li	Cu	Zn	Ag	Density (*1000 kg/m3)
Alloy 1	5.76	2.26	—	—	—	2.47
Alloy 2	4.65	1.55	—	—	—	2.53
Alloy 3	3.83	1.94	—	—	—	2.52
Alloy 4	4.54	1.87	—	—	—	2.51
Alloy 5	5.54	1.89	—	—	—	2.5
Alloy 6	4.63	1.67	—	1.54	—	2.54
Alloy 7	4.71	1.58	—	—	0.66	2.54
Alloy 8	4.61	1.64	0.53	1.54	—	2.56

Alloy **1** is based on conventional Russian alloy 01420 (the "1420" alloy). All of Alloys **1**-**8** contain not greater than 0.04 wt. % Si, not greater than 0.06 wt. % Fe, not greater than 0.04 wt. % Mn, and from 0.10 to 0.12 wt. % Zr, the balance being aluminum and other elements, the other elements not exceeding 0.05 wt. % each, and the combined amount of the other elements not totaling more than 0.15 wt. %.

[0024] After casting, all of the alloys were scalped, homogenized (preheated), and then hot rolled to final gauge of about 0.25 inch, after which the alloys were allowed to cool to room temperature. Next, the alloys were solution heat treated and quenched, after which the alloys were stretched about 3%, and then aged at 300° F. for various times, placing the alloys in a T8 temper. The mechanical properties of the aged samples were then tested in accordance with ASTM E8 and B557, the results of which are shown in Table 2, below, and illustrated in FIGS. **1***a***1**-*c* (all values averages of duplicate test specimens).

TABLE 2

Example 1 Alloys - Longitudinal (L)
Strength and Elongation Properties

Alloy Number	Aging Time (hours)	TYS (L) (ksi)	UTS (L) (ksi)	Elongation (L) (%)
Alloy 1	0	34.3	55.05	26
Alloy 1	16	47.55	69.5	14
Alloy 1	24	48.5	69.75	14
Alloy 1	40	49.5	70.75	14
Alloy 2	0	35.1	46.4	26
Alloy 2	16	41.05	56.6	18
Alloy 2	24	41	57.1	18
Alloy 2	40	41.2	57	18
Alloy 3	0	32.95	43.75	25

TABLE 2-continued

Example 1 Alloys - Longitudinal (L) Strength and Elongation Properties

Alloy Number	Aging Time (hours)	TYS (L) (ksi)	UTS (L) (ksi)	Elongation (L) (%)
Alloy 3	16	41	57.75	17
Alloy 3	24	41.4	58.2	15.5
Alloy 3	40	41.9	59.5	14
Alloy 4	0	35.5	49.3	24
Alloy 4	16	43	61.9	16
Alloy 4	24	45	63.5	16
Alloy 4	40	44.7	63.35	15.5
Alloy 5	0	36.7	53.85	26
Alloy 5	16	46.75	66.7	15
Alloy 5	24	47.25	67.35	15.5
Alloy 5	40	47.8	68.6	16
Alloy 6	0	36	48.85	24
Alloy 6	16	49.1	64.75	14.5
Alloy 6	24	49.7	66.3	12
Alloy 6	40	50.3	67.95	13
Alloy 7	0	35.8	45.95	24
Alloy 7	16	45.25	57.55	16
Alloy 7	24	46.45	59.85	16
Alloy 7	40	46.15	60	16
Alloy 8	0	38.85	52.55	24
Alloy 8	16	50.9	65.6	17
Alloy 8	24	54.75	69.95	14
Alloy 8	40	53.15	69.7	14

[0025] Next, long transverse (LT) strength T-L plane strain fracture toughness tests were performed on the 24-hour aged alloy samples, the results of which are shown in Table 3, below, and illustrated in FIG. **1***d*.

TABLE 3

Example 1 Alloys - Long Transverse (LT) Strength and T-L Toughness Properties

Alloy	Tensile Yield Strength (LT) (ksi)	T-L plane strain fracture toughness (ksi✓in.)
Alloy 1	48.4	21.6
Alloy 2	41	23.6
Alloy 3	41.4	22.3
Alloy 4	45	22.5
Alloy 5	47.2	24.9
Alloy 6	49.7	31.2

TABLE 3-continued

Example 1 Alloys - Long Transverse (LT) Strength and T-L Toughness Properties

Alloy	Tensile Yield Strength (LT) (ksi)	T-L plane strain fracture toughness (ksi✓in.)
Alloy 7	46.4	21.9
Alloy 8	54.8	26.4

[0026] As shown above, and in FIGS. **1***a*-**1***d*, alloys having zinc and/or copper additions realize improved properties over conventional Russian alloy 1420 (Alloy **1**). Indeed, as shown in FIGS. **1***a*-**1***c*, Alloys **6** and **8**, both achieve improved tensile yield strength over Alloy **1** (FIG. **1***a*), and with comparable ultimate tensile strength (**1***b*) and elongation (**1***c*). As shown in FIG. **1***d*, Alloys **6** and **8** realize an improved strength-toughness combination over Alloy **1**.

EXAMPLE 2

[0027] Various 5xxx-lithium aluminum alloys were cast in book molds to make ingots, and then processed to a 0.25 inch (approx.) rolled product in the T8 temper per Example 1, above. The alloy compositions are provided in Table 4, below.

TABLE 4

Example 2 Alloy Compositions and Density

Alloy Number	Mg	Li	Zn	Cu	Ag	Density (*1000 kg/m3)	Cu + Ag	Invention Alloy?
9	4.32	2.02	0.95	0.345	0.23	2.51	0.575	Yes
10	4.33	2.11	1.85	0.355	0.235	2.53	0.59	Yes
11	4.53	2.095	0.97	0.955	0.245	2.53	1.2	No
12	4.405	2.105	1.910	0.935	0.24	2.54	1.175	No
13	4.405	2.17	0.096	0.345	0.65	2.51	0.995	Yes
14	4.365	1.995	1.87	0.355	0.655	2.55	1.01	Yes
15	4.355	1.99	0.975	0.955	0.66	2.55	1.615	No
16	4.375	2.065	1.895	0.895	0.625	2.55	1.52	No
17	4.395	2.025	1.455	0.66	0.44	2.54	1.065	Yes
18	4.285	2.14	2.82	0.635	0.43	2.56	2.325	No
19	4.43	2.115	1.435	1.875	0.45	2.56	1.595	No
20	4.44	2.12	1.49	0.675	0.92	2.55	1.11	No
21*	4.445	1.975	1.44	0.665	0.445	2.54	1.11	Yes
22*	4.395	2.09	1.45	0.665	0.445	2.53	1.065	No

Unless otherwise noted below, all of Alloys **9**-**22** contain not greater than 0.04 wt. % Si, not greater than 0.06 wt. % Fe, not greater than 0.04 wt. % Mn, not greater than 0.02 wt. % Ti (added as a grain refiner), from 0.10 to 0.13 wt. % Zr, the balance being aluminum and other elements, the other elements not exceeding 0.05 wt. % each, and the combined amount of the other elements not totaling more than 0.15 wt. %.

[0028] Alloy **21** contained 0.24 wt. % Si.

[0029] Alloy **22** contained 0.89 wt. % Si.

[0030] The mechanical properties of the aged samples were then tested in accordance with ASTM E8 and B557, the results of which are shown in Tables 5-6, below (values aver-

ages of duplicate test specimens), and some of which are illustrated in FIGS. **2***a*-**1** through **2***d*-**2**. As shown, the invention alloys (**9-10**, **13-14**, **17** and **21**) realize an improved strength-toughness relationship, and contain from 4.32 to 4.45 wt. % Mg, from 1.975 to 2.17 wt. % Li, and from 0.95 to 1.87 wt. % Zn. The invention alloys also all contain an amount of Cu+Ag that does not exceed 1.11 wt. %. The invention alloys also contain up to 0.24 wt. % Si. The non-invention alloys (**11-12**, **15-16**, **18**, **20** and **22**) either contain too much Cu+Ag (alloys **11-12**, **15-16**, **18**, **20**) or contain too much silicon (alloy **22**). These best performing alloys contain about 0.35 wt. % Cu and with from about 0.2 to about 0.7 wt. % Ag.

TABLE 5

Example 2 Alloys - Longitudinal (L) Strength and Elongation Properties

Alloy Number	Aging Time (hours)	Aging Temp. (F.)	Tensile Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)
Alloy 9	0	300	27.2	56	23
Alloy 9	0	300	26.9	52.4	25
Alloy 9	10	300	44.9	68.1	15
Alloy 9	10	300	44.6	67.3	14
Alloy 9	16	300	46.2	68.2	14
Alloy 9	16	300	46.3	69.4	14
Alloy 9	24	300	48.8	72.9	12
Alloy 9	24	300	47.7	70.9	12
Alloy 9	40	300	46	67.7	14
Alloy 9	40	300	47.8	69.9	12
Alloy 10	0	300	29.6	54.8	24
Alloy 10	0	300	28.5	56	24
Alloy 10	10	300	48.9	69.8	11
Alloy 10	10	300	49	67.9	10
Alloy 10	16	300	50.6	72.6	11
Alloy 10	16	300	49.5	69.7	10
Alloy 10	24	300	51.8	71.7	9
Alloy 10	24	300	51.4	72.3	10
Alloy 10	40	300	53.8	71.4	10
Alloy 10	40	300	52.5	70.6	8
Alloy 11	0	300	28.6	50.1	20
Alloy 11	0	300	28.8	50.5	20
Alloy 11	10	300	45.9	64.4	10
Alloy 11	10	300	46.8	64	10
Alloy 11	16	300	46.9	65.1	10
Alloy 11	16	300	47.3	65.1	10
Alloy 11	24	300	49.2	65.6	9
Alloy 11	24	300	47.8	65.4	9
Alloy 11	40	300	48.4	66	8
Alloy 11	40	300	49.5	66.7	8
Alloy 12	0	300	27.9	49.8	16
Alloy 12	0	300	27.9	50.1	17
Alloy 12	10	300	45.2	63.3	10
Alloy 12	10	300	45.8	62.3	9
Alloy 12	16	300	47.6	63.4	9
Alloy 12	16	300	46.2	62.9	8
Alloy 12	24	300	46.8	64.1	8
Alloy 12	24	300	47.1	63.5	7
Alloy 12	40	300	48.1	63	7
Alloy 12	40	300	47.6	63.8	7
Alloy 13	0	300	27.7	54.7	21
Alloy 13	0	300	28.4	53.4	23
Alloy 13	10	300	46.7	67.3	13
Alloy 13	10	300	46.1	67.9	11
Alloy 13	16	300	46.5	68.5	11
Alloy 13	16	300	45.2	68.9	11
Alloy 13	24	300	47.9	68.4	9
Alloy 13	24	300	48	71.3	10
Alloy 13	40	300	49.9	70.7	10
Alloy 13	40	300	49.4	70.4	10
Alloy 14	0	300	29.5	51.9	20
Alloy 14	0	300	29.5	52.9	20
Alloy 14	10	300	48.1	65.8	14

TABLE 5-continued

Example 2 Alloys - Longitudinal (L) Strength and Elongation Properties

Alloy Number	Aging Time (hours)	Aging Temp. (F.)	Tensile Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)
Alloy 14	10	300	49	65.6	11
Alloy 14	16	300	50.8	66.8	9
Alloy 14	16	300	49.3	66.9	12
Alloy 14	24	300	51.1	68	9
Alloy 14	24	300	51.2	66.8	9
Alloy 14	40	300	51.7	65.3	7
Alloy 14	40	300	52.7	66.9	7
Alloy 15	0	300	27	47.7	17
Alloy 15	0	300	27.3	47.4	21
Alloy 15	10	300	44	59.7	8
Alloy 15	10	300	45.3	59.7	8
Alloy 15	16	300	45.3	61.8	10
Alloy 15	16	300	46	61.5	9
Alloy 15	24	300	46.8	62.3	8
Alloy 15	24	300	46.5	62.7	10
Alloy 15	40	300	48	62.9	10
Alloy 15	40	300	47.2	62.9	9
Alloy 16	0	300	28.4	48.6	15
Alloy 16	0	300	27.2	47.1	15
Alloy 16	10	300	44.3	59.5	8
Alloy 16	10	300	45	58.4	8
Alloy 16	16	300	45.4	59.2	7
Alloy 16	16	300	45.8	59.7	7
Alloy 16	24	300	47.5	61.5	9
Alloy 16	24	300	46	61.2	7
Alloy 16	40	300	47.4	61.4	8
Alloy 16	40	300	46.9	61	6
Alloy 17	0	300	28.5	48.8	20
Alloy 17	0	300	28	49.9	20
Alloy 17	10	300	46.7	62.9	11
Alloy 17	10	300	45.6	61.9	11
Alloy 17	16	300	46.7	64.6	11
Alloy 17	16	300	46.2	62.9	9
Alloy 17	24	300	47	65.1	9
Alloy 17	24	300	47.5	65.5	10
Alloy 17	40	300	48.3	65.1	10
Alloy 17	40	300	47.7	64	8
Alloy 18	0	300	27.6	48	14
Alloy 18	0	300	26.9	48.5	19
Alloy 18	10	300	45	58.5	7
Alloy 18	10	300	46.1	61	10
Alloy 18	16	300	46.4	59.1	6
Alloy 18	16	300	46.7	60.3	8
Alloy 18	24	300	45.8	61	7
Alloy 18	24	300	47	62	8
Alloy 18	40	300	47.9	60.7	6
Alloy 18	40	300	49.4	62.4	8
Alloy 19	0	300	27	48.6	19
Alloy 19	0	300	26.6	47.8	15
Alloy 19	10	300	45.7	60.3	12
Alloy 19	10	300	44.5	60.1	12
Alloy 19	16	300	45.4	59.7	8
Alloy 19	16	300	45.5	60.2	7
Alloy 19	24	300	46.2	61	7
Alloy 19	24	300	46.4	61.3	7
Alloy 19	40	300	46.7	62.3	8
Alloy 19	40	300	48	62.7	8
Alloy 20	0	300	28.8	47.4	15
Alloy 20	0	300	29.4	47.7	15
Alloy 20	10	300	47.2	60.3	8
Alloy 20	10	300	46.3	58.2	6
Alloy 20	16	300	47.7	60.3	6
Alloy 20	16	300	48.6	60.9	7
Alloy 20	24	300	49.2	60.6	6
Alloy 20	24	300	49.9	60.7	5
Alloy 20	40	300	48.8	61.4	5
Alloy 20	40	300	50	61.7	5
Alloy 21	0	300	28.1	48.5	19
Alloy 21	0	300	27	48	21

TABLE 5-continued

Example 2 Alloys - Longitudinal (L) Strength and Elongation Properties

Alloy Number	Aging Time (hours)	Aging Temp. (F.)	Tensile Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)
Alloy 21	10	300	42.7	60.8	11
Alloy 21	10	300	42.8	60.7	10
Alloy 21	16	300	43.7	61.6	9
Alloy 21	16	300	44.6	61.5	10
Alloy 21	24	300	47.1	63.6	10
Alloy 21	24	300	45.3	61.8	9
Alloy 21	40	300	46	62.9	9
Alloy 21	40	300	45.7	62.8	9
Alloy 22	0	300	28.8	47.7	20
Alloy 22	0	300	28	47	19
Alloy 22	10	300	45.1	60.5	9
Alloy 22	10	300	45.6	60.1	9
Alloy 22	16	300	47.3	60.8	9
Alloy 22	16	300	47.3	60.9	9
Alloy 22	24	300	48.5	62.6	9
Alloy 22	24	300	48.3	61.3	7
Alloy 22	40	300	49.2	62	7
Alloy 22	40	300	48.4	62.4	7

TABLE 6

Example 2 Alloys - Long Transverse (LT) Strength and T-L Toughness Properties (aged at 300° F. for 24 hours, except for Alloy 9, which was aged at 300° F. for 10 hours)

Alloy	Tensile Yield Strength (LT) (ksi)	Ultimate Tensile Strength (LT) (ksi)	Elongation (LT) (%)	T-L plane strain fracture toughness (ksi✓in.)
Alloy 9	45.85	69.25	9	35.7
Alloy 10	52.75	72.2	8	31.9
Alloy 11	49.2	65.85	7	26.2
Alloy 12	47.7	64.55	9	22.9
Alloy 13	49.3	71.1	10.5	32.6
Alloy 14	51.6	67.8	8.5	28.1
Alloy 15	49	60.25	5.5	25
Alloy 16	48.65	62.85	8	24.7
Alloy 17	49.7	66.35	9	26.4
Alloy 18	49.35	61.35	5	20.8
Alloy 19	51.15	62.6	8.5	21.5
Alloy 20	47.9	61.3	6.5	24.3
Alloy 21	45.9	61.25	7	31.1
Alloy 22	49.95	62.3	7	22.5

[0031] While various embodiments of the new technology described herein 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 presently disclosed technology.

1. An aluminum alloy consisting of:

from 3.75 to 5.0 wt. % magnesium (Mg);

from 1.6 to 2.3 wt. % lithium (Li);

from 0.50 to 2.5 wt. % zinc (Zn);

0.05 to 0.50 wt. % of a grain structure control element selected from the group consisting of zirconium (Zr), scandium (Sc), chromium (Cr), vanadium (V), hafnium (Hf), other rare earth elements, and combinations thereof;

up to 1.00 wt. % copper (Cu);

up to 1.00 wt. % silver (Ag);

wherein Cu+Ag≥1.15 wt. %;

wherein, when the aluminum alloy contains not greater than 0.04 wt. % Cu and not greater than 0.04 wt. % Ag, the aluminum alloy contains at least 0.75 wt. % zinc;

up to 0.5 wt. % silicon (Si);

up to 1.0 wt. % manganese (Mn);

up to 0.15 wt. % titanium (Ti); and

the balance being aluminum, other elements and impurities, wherein the aluminum alloy contains not greater than 0.10 wt. % of any one of the other elements, and wherein the aluminum alloy contains not greater than 0.35 wt. % total of the other elements.

2. The aluminum alloy of claim **1**, wherein the aluminum alloy contains at least 40 wt. % Mg.

3.-**5**. (canceled)

6. The aluminum alloy of claim **2**, wherein the aluminum alloy contains not greater than 4.9 wt. % Mg.

7.-**9**. (canceled)

10. The aluminum alloy of claim **1**, wherein the aluminum alloy contains at least 1.65 wt. % Li.

11.-**12**. (canceled)

13. The aluminum alloy claim **10**, wherein the aluminum alloy contains not greater than 2.20 wt. % Li.

14. (canceled)

15. The aluminum alloy of claim **1**, wherein the aluminum alloy contains at least 0.60 wt. % Zn.

16.-**19**. (canceled)

20. The aluminum alloy of claim **15**, wherein the aluminum alloy contains not greater than 2.25 wt. % Zn.

21. (canceled)

22. The aluminum alloy of claim **1**, wherein the aluminum alloy contains at least 0.05 wt % Cu.

23.-**25**. (canceled)

26. The aluminum alloy of claim **22**, wherein the aluminum alloy contains not greater than 0.90 wt. % Cu.

27.-**29**. (canceled)

30. The aluminum alloy of claim **1**, wherein the aluminum alloy contains at least 0.05 wt. % Ag.

31.-**33**. (canceled)

34. The aluminum alloy of claim **30**, wherein the aluminum alloy contains not greater than 0.90 wt. % Ag.

35.-**37**. (canceled)

38. The aluminum alloy of claim **1**, wherein the aluminum alloy contains not greater than 1.10 wt. % Cu+Ag.

39.-**40**. (canceled)

41. The aluminum alloy of claim **1**, wherein the aluminum alloy contains at least 0.05 wt. % of at least one of Cu and Ag, and wherein the new aluminum alloy contains at least 0.15 wt. % Cu+Ag.

42.-**46**. (canceled)

47. The aluminum alloy of claim **1**, wherein the aluminum alloy contains not greater than 0.35 wt. % Si.

48. (canceled)

49. The aluminum alloy of claim **47**, wherein the aluminum alloy contains at least 0.05 wt. % Si.

50. The aluminum alloy of claim **1**, wherein the aluminum alloy contains not greater than 0.75 wt. % Mn.

51.-**52**. (canceled)

53. The aluminum alloy of claim **50**, wherein the aluminum alloy contains at least 0.20 wt. % Mn.

54.-**55**. (canceled)

56. The aluminum alloy of claim **1**, wherein the grain structure control element comprises zirconium, and wherein the aluminum alloy contains from 0.05 wt. % to 0.20 wt. % Zr.

57.-**59**. (canceled)

60. The aluminum alloy of claim **56**, wherein the aluminum alloy contains from 0.01 to 0.10 wt. % Ti.

61.-**62**. (canceled)

63. The aluminum alloy of claim **60**, wherein the impurities comprise iron (Fe), and wherein the aluminum alloy contains not greater than 0.25 wt. % Fe.

64.-**71**. (canceled)

* * * * *