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# (54) NEW AL-CU-LI-MG-AG-MN-ZR ALLOY FOR USE AS STRUCTURAL MEMBERS REQUIRING HIGH STRENGTH AND HIGH FRACTURE TOUGHNESS

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## (57) ABSTRACT

An improved aluminum lithium alloy comprising 0.1 to 2.5 wt. % Li, 2.5 to 5.5 wt. % Cu, 0.2 to 1.0 wt. % Mg, 0.2 to 0.8 wt. % Ag, 0.2 to 0.8 wt. % Mn, up to 0.4 wt. % Zr or other grain refiner such as chromium, titanium, hafnium, scandium or vanadium, the balance aluminum. The present alloy exhibits an improved combination of strength and fracture toughness, over any thickness range. The present invention is further directed to methods for preparing and using Al—Li alloys as well as to products comprising the same.

# NEW AL-CU-LI-MG-AG-MN-ZR ALLOY FOR USE AS STRUCTURAL MEMBERS REQUIRING HIGH STRENGTH AND HIGH FRACTURE TOUGHNESS

## CROSS REFERENCE TO RELATED APPLICATIONS

**[0001]** The present application is a continuation of U.S. Ser. No. 10/853,721 filed May 26, 2004 which claims priority from U.S. Provisional Ser. No. 60/473,443, filed May 28, 2003, the content of each are incorporated herein by reference in their entirety.

## BACKGROUND OF THE INVENTION

**[0002]** 1. Field of the invention

**[0003]** The present invention relates to aluminum-lithium based alloy products, particularly those suitable for use as structural members in aircraft construction, such as in bulkhead, spars, wing skin, frames, extruded structural members, and fuselage applications, as well as other applications where a combination of high strength and high fracture toughness are typically desirable and/or required.

**[0004]** 2. Description of Related Art

**[0005]** In many industries and particularly in the aircraft industry, reducing the weight of structures has always been a concern. One effective way of doing this is to reduce the density of aluminum alloys used in such structures. It is well known in the art that aluminum alloy densities may be reduced by the addition of lithium. However, it is also known that some problems arise when lithium is added to aluminum based alloys. One of the problems encountered is the possible decrease in ductility and fracture toughness.

**[0006]** Most structural applications in the aircraft industry, and particularly applications such as products intended for use in lower wing skin structures, require a high level of strength, as well as a high level of fracture toughness. It is also desirable for aircraft and other similar applications, that ductility and corrosion behavior remain at an acceptable level.

**[0007]** Among aluminum-lithium based alloys, Al—Cu—Li—Mg—Ag alloys are well-known in the prior art for their interesting properties. Specifically, U.S. Pat. No. 5,032,359 discloses an alloy with a broad composition of 2.0 to 9.8 wt. % of an alloying element, which may be copper, magnesium, or mixtures thereof, the magnesium being at least 0.05 wt. %, from about 0.01 to about 2.0 wt. % silver, from about 0.2 to about 4.1 wt. % lithium, and from about 0.05 to about 1.0 wt. % of a grain refining additive selected from zirconium, chromium, manganese, titanium, boron, hafnium, vanadium, titanium diboride, and mixtures thereof.

**[0008]** U.S. Pat. No. 5,389,165 discloses a preferred composition of 1.10 wt. % Li, 3.61 wt. % Cu, 0.33 wt. % Mg, 0.40 wt. % Ag and 0.14 wt. % Zr. An alloy composition corresponding to such a range was registered at The Aluminum Association in June 2000 as AA 2098. This alloy exhibits high fracture toughness and strength at elevated temperatures, after having been subjected to a specific process. An alloy as disclosed in the '165 patent may be suitable for some thin or medium gauge plate products used in aircraft structures, but may be less suitable for use as thick gauge plates, because of rather low mechanical properties in the ST direction.

**[0009]** Another aluminum-lithium based alloy has also been proposed for thick gauges. This alloy, registered at The Aluminum Association as AA 2297 in August 1997, contains lithium, copper, manganese, and optionally magnesium, but no silver. U.S. Pat. No. 5,234,662 discloses a preferred composition of 1.6 wt. % Li, 3.0 wt. % Cu, 0.3 wt. % Mn, 0.12 wt. % Zr. The alloy, produced in thick gauges, exhibits a good combination of low density, strength, toughness, fatigue resistance and corrosion resistance.

## SUMMARY OF THE INVENTION

**[0010]** An object of the present invention was to provide a low density, high strength, high fracture toughness aluminum alloy, which advantageously contains lithium, copper, magnesium, silver, manganese, and a grain refiner, preferably zirconium. Alloys of the present invention are particularly suitable for many if not all structural applications in aircraft, over a wide range of product thicknesses. Because the inventive alloy exhibits improved properties in virtually any thickness range, the inventive product can be used in virtually all forms and for all applications, such as sheets, plates, forgings and extrusions. It can also be machined to form structural members such as spars; it is also suitable for use in welded assemblies.

**[0011]** The present invention comprises an Al—Cu—Li—Mg—Ag—Mn—Zr alloy and demonstrates an unexpected and surprising effect, inter alia, relating to the addition of a small amount of manganese to Al—Cu—Li—Mg—Ag—Zr alloys. The addition of a small amount of Mn to an Al—Cu—Li—Mg—Ag—Zr alloy improves the fracture toughness of the alloy at a similar strength level.

**[0012]** Thus, there is provided by the present invention an improved aluminum lithium alloy comprising 0.1 to 2.5 wt. % Li, 2.5 to 5.5 wt. % Cu, 0.2 to 1.0 wt. % Mg, 0.2 to 0.8 wt. % Ag, 0.2 to 0.8 wt. % Mn, up to 0.4 wt. % Zr and/or other grain refiner such as chromium, titanium, hafnium, scandium or vanadium, with the balance aluminum and inevitable elements and impurities such as silicon, iron and zinc. The present alloy exhibits an improved combination of strength and fracture toughness, over virtually any thickness range.

**[0013]** The present invention is further directed to methods for preparing and using Al—Li alloys as well as to products comprising the same.

**[0014]** Additional objects, features and advantages of the invention will be set forth in the description which follows, and in part, will be obvious from the description, or may be learned by practice of the invention. The objects, features and advantages of the invention may be realized and obtained by means of the instrumentalities and combination particularly pointed out in the appended claims.

## DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

**[0015]** In the present invention, it was discovered that minor additions of manganese to Al—Cu—Mg—Ag alloys suitable for thin gauges, such as AA 2098, unexpectedly provided improved results, inter alia in terms of fracture toughness. It was also discovered that a minor addition of magnesium or silver to Al—Cu—Li—Mn—Zr alloys such as AA 2297, which is more suitable for thick gauges, also unexpectedly provided improved strength while possessing similar or even higher fracture toughness. Potentially even more importantly, the present alloy has improved strength and fracture toughness in the ST direction, which is very often a critical direction for certain applications such as very thick plates applications. Therefore, the present inventive alloy, which in some embodiments comprises certain preferred amounts of magnesium, silver and manganese, surprisingly shows better properties in thin,-medium and thick gauge applications, than the closest alloys from the prior art.

**[0016]** A copper content between about 3 to about 4 wt. %, and a lithium content between 0.8 and 1.5 wt. % are preferred. In one preferred embodiment, the lithium content is between about 0.9 and about 1.3 wt. %. In the new inventive alloy, magnesium in the range of about 0.2 to about 1 wt. %, preferably from 0.3 to 0.5 wt. %, silver in the range of about 0.2 to about 0.8 wt. % and preferably from 0.3 to 0.5 wt. %, and manganese in the range of about 0.2 wt. % to about 0.8 wt. %, and preferably from 0.3 to 0.5 wt. %, produces an alloy having surprisingly high strength and high fracture toughness. This will become apparent in the examples provided below, where the new alloy will be compared to Al—Cu—Li—Mg—Ag—Zr alloy products such as AA 2098 alloy products, which are used for thin gauge products, and will also be compared to Al—Cu—Li—Mn—Zr alloy products such as AA 2297 alloy products, which are currently used for thick gauge products.

**[0017]** The composition of the present inventive alloy may also optionally include minor amounts of grain refinement elements such as zirconium, chromium, titanium, hafnium, scandium and/or vanadium, that is, particularly up to about 0.3wt. % of Zr, up to about 0.8 wt. % of Cr, up to about 0.12 wt % of Ti, up to about 1.0 wt. % of Hf, up to about 0.8 wt. % of Sc, up to about 0.2 wt. % of V are envisioned. A zirconium content between about 0.05 and 0.15 wt. % is preferred. In one preferred embodiment, the total amount of grain refining elements advantageouly does not exceed about 0.25 wt. %. A preferred embodiment of the present invention is an alloy comprising between about 0.8 and about 1.2 wt. % of lithium.

**[0018]** The present alloy is preferably provided as an ingot or billet by any suitable casting technique known in the art. Ingots or billets may be preliminary worked or shaped if desired for any reason to provide suitable stock for subsequent operations. The alloy stock can then be processed in a classical way, such as by performing one or more homogenization operations, hot rolling steps, solution heat treatment, a water quench, stretching, and one or more aging steps to reach peak strength.

**[0019]** According to the present invention, it is possible to obtain a thick (typically at least about 3 inches (76.2 mm) thick) aluminum based alloy product that exhibits in a solution heat—treated, quenched, stress-relieved and artificially aged condition, at least one set of properties selected from the group consisting of:

**[0020]** (a) UTS (L)>70 ksi (482.6 MPa) and $K_{IC}$ (L)>34 ksi √inch (37.4√MPa√m)

**[0021]** (b) TYS (L)>65 ksi (448.2 MPa) and $K_{IC}$ (L)>34 ksi √inch (37.4 MPa√m)

**[0022]** (c) UTS (LT)>70 ksi (482.6 MPa) and $K_{IC}$ (L-T)>27 ksi √inch (29.7 MPa√m)

**[0023]** (d) TYS (LT)>62 ksi (427.5 MPa) and $K_{IC}$ (L-T)>26 ksi √inch (28.6 MPa√m)

**[0024]** (e) UTS (ST)>70 ksi (482.6 MPa) and $K_{IC}$ (S-T)>24 ksi √inch (06.4 MPa√m)

**[0025]** (f) TYS (ST)>60 ksi (413.7 MPa) and $K_{IC}$ (S-T)>23 ksi √inch (25.3 MPa√m).

**[0026]** According to another embodiment of the present invention, it is possible to obtain an aluminum based alloy rolled product with a thickness of less than about 3 inches, that exhibits in a solution heat-treated, quenched, stress-relieved and artificially aged condition, at least one set of properties selected from the group consisting of

**[0027]** (a) UTS (L)>76 ksi (524.0 MPa) and $K_{IC}$ (L)>35 ksi √inch (38.5 MPa√m)

**[0028]** (b) TYS (L)>71 ksi (489.5 MPa) and $K_{IC}$ (L)>35 ksi √inch (38.5 MPa√m)

**[0029]** (c) UTS (LT)>75 ksi (517.1 MPa) and $K_{IC}$ (L-T)>29 ksi √inch (31.9 MPa√m)

**[0030]** (d) TYS (LT)>68 ksi (468.8 MPa) and $K_{IC}$ (L-T)>29 ksi √inch (31.9 MPa√m)

**[0031]** (e) UTS (ST)>76 ksi (524.0 MPa) and $K_{IC}$ (S-T)>26 ksi √inch (28.6 MPa√m)

**[0032]** (f) TYS (ST)>65 ksi (448.2 MPa) and $K_{IC}$ (S-T)>26 ksi √inch (28.6 MPa√m).

**[0033]** The following examples are provided to illustrate the invention but the invention is not to be considered as being limited thereto. In these examples and throughout this specification, parts are by weight unless otherwise indicated. Also, compositions include normal and/or inevitable impurities, such as silicon, iron and zinc. Example 1

**[0034]** An alloy according to the invention, referenced Al, was produced in gauge 2.5 inches, and compared to an Al—Cu—Li—Mg—Ag—Zr (AA 2098) alloy plate, referenced B1. Actual compositions of cast alloy A1 and B1 products are provided in Table 1 below. Alloy B1 was produced in thinner gauge of 1.7 inches (43.2 mm), because the properties of this alloy in 2.5 inch (63.5 mm) gauge, especially its fracture toughness in ST direction are too poor to enable the product to be a viable commercial product.

**[0035]** Alloy Al product was processed according to a prior art practice to obtain a plate in a peak aged temper. Namely, alloy Al product was homogenized for 24 hours at 980° F. (526.7° C.), hot rolled at a temperature range of 780 to 900° F. (415.6-482.2° C.) to obtain a n2.5 inch (63.5 mm) gauge, then solution heat treated at 980° F. (526.7° C.) for 2 hours, then water quenched, stretched at a level of 3%, and artificially aged for 48 hours at 290° F. (155.3° C.) in order to reach the peak strength (T8 temper).

**[0036]** Alloy B1 plate was also homogenized for 24 hours at 980° F. (526.7° C.), hot rolled at a temperature range of 780 to 900° F. (415.6-482.2° C.) to obtain a 1.7 inches (43.2 mm) thick plate, then solution heat treated at 980° F. (526.7° C.) for 2 hours, water quenched, stretched at a level of 3%, and artificially aged for 17 hours at 320° F. (160.0° C.), in order to reach the peak strength (T8 temper).

**[0037]** Respective Ultimate Tensile strength (UTS), Tensile Yield Strength (TYS), and Elongation (E) of alloy A1 and B1 samples were determined in L, LT, and ST directions according to ASTM B557. The fracture toughness of alloy A1 and B1 were determined, using the method of evaluation of the plain-strain Fracture Toughness ($K_{IC}$), according to ASTM E399. This method is appropriate when in plain-strain deformation, which is applicable for the samples analyzed in this example, since these samples are relatively thick (over 1 inch (25.4 mm) thick). All results for alloy A1 and B1 samples are provided in Table 2 below. Most of these values are average values for two duplicate tests on the same plate sample.

TABLE 1

Compositions of cast alloys A1 and B1 in wt. %

| | Cu | Li | Mg | Ag | Zr | Mn |
|---|---|---|---|---|---|---|
| Alloy A1 sample (invention) | 3.59 | 0.9 | 0.34 | 0.30 | 0.09 | 0.43 |
| Alloy B1 sample | 3.58 | 0.99 | 0.34 | 0.34 | 0.14 | <0.01 |

**[0038]**

TABLE 2

Mechanical Properties of inventive alloy A1 (thickness 2.5 inches (63.5 mm)) compared to alloy B1 (thickness 1.7 inches (43.2 mm))

| | Direction of Measurement | UTS (ksi) [MPa] | TYS (ksi) [MPa] | E (%) | $K_{IC}$ (ksi √$\sqrt{\text{inch}}$) [MPa√$\sqrt{\text{m}}$] |
|---|---|---|---|---|---|
| Sample A1 - 2.5 inches (63.5 mm) thick (invention) | L | 80.6 [555.7] | 77.0 [530.9] | 10 | 39.5 [43.4] |
| | LT | 78 [537.8] | 71.0 [489.5] | 9.5 | 30.9 [34.0] |
| | ST | 77.9 [537.1] | 67.0 [462.0] | 5.6 | 27.5 [30.2] |
| Sample B1 - 1.7 inches (43.2 mm) Thick | L | 80.6 [555.7] | 76.3 [526.1] | 14.5 | 31.1 [34.2] |
| | LT | 80.5 [555.0] | 74 [510.2] | 11 | 28.4 [31.2] |
| | ST | 83.3 [574.3] | 70.3 [484.7] | 6.4 | 24.9 [27.4] |

**[0039]** The alloy plate according to the invention exhibits better fracture toughness in all three directions, as compared with those from sample B1 from the prior art, with similar strengths in L, LT and ST directions. Fracture Toughness of the present alloy is unexpectedly improved by up to 27% in the L direction (or even greater), by up to or more than 10% in the ST direction, and by up to or more than 8% in the LT direction. Example 2

**[0040]** An Al—Cu—Li—Mn—Zr alloy plate from the prior art (AA 2297 alloy), referenced B2, was produced in a thicker gauge than in example 1; namely thickness of plate B2 was 5 inches (127 mm). Alloy B2 plate was compared to alloy A1 according to the invention, which was also produced in thicker gauge, namely 5 inches (127 mm). Samples of A1 alloy in 5 inches (127 mm) gauge are referenced as A2 in this example. The actual composition of cast alloy A2 and B2 products is provided in Table 3 below.

**[0041]** Alloy A2 plate was processed according to a prior art practice to obtain a plate in T8 temper. Namely, alloy A2 ingot was homogenized for 24 hours at 980° F. (526.7° C.), hot rolled at a temperature range of 800 to 900° F. (426.7-482.2° C.), then solution heat treated at 980° F. (526.7° C.) for 3.5 hours, then water quenched, stretched at a level of 3%, and artificially aged for 40 hours at 290° F. (143.3° C.) in order to reach the peak strength (T8 temper).

**[0042]** Alloy B2 plate was also processed according to a prior art practice to obtain a plate in T8 temper. Namely, alloy B2 plate was homogenized for 24 hours at 980° F. (526.7° C.), hot rolled at a temperature range of 800 to 900° F. (426.7-482.2° C.), then solution heat treated at 980° F. (526.7° C.) for 3.5 hours, water quenched, stretched at a level of 6%, and artificially aged for 22 hours at 320° F. (160° C.), in order to reach the peak strength (T8 temper).

**[0043]** Respective Ultimate Tensile strength (UTS), Tensile Yield Strength (TYS), and Elongation (E) of alloy A2 and alloy B2 samples were determined in L, .LT, and ST directions according to ASTM B557. The fracture toughness of alloy A2 and B2 were determined, using the well-known method of evaluation of the plain-strain Fracture Toughness ($K_{IC}$), according to ASTM E399. All results for alloy A2 and 132 samples are provided in Table 4 below.

TABLE 3

Compositions of cast alloys A2 and B2

| | Cu | Li | Mg | Ag | Zr | Mn |
|---|---|---|---|---|---|---|
| Alloy A2 sample (invention) | 3.59 | 0.9 | 0.34 | 0.30 | 0.09 | 0.43 |
| Alloy B2 sample | 2.89 | 1.17 | — | — | 0.10 | 0.31 |

**[0044]**

TABLE 4

Mechanical properties of inventive alloy A2 in 5 inches (127 mm) gauge compared to prior art alloy B2 in 5 inches (127 mm) gauge

| | Direction of Measurement | UTS (ksi) [MPa] | TYS (ksi) [MPa] | E (%) | $K_{IC}$ (ksi √$\sqrt{\text{inch}}$) [MPa√$\sqrt{\text{m}}$] |
|---|---|---|---|---|---|
| Sample A1 - thick gauge (invention) | L | 73.5 [506.8] | 68.8 [474.4] | 10.8 | 36.0 [39.6] |
| | LT | 73.8 [508.8] | 65 [448.2] | 8.8 | 28.3 [31.1] |
| | ST | 74.3 [512.3] | 64 [441.3] | 6.5 | 26.9 [29.6] |
| Sample B2 - thick gauge | L | 62.4 [430.2] | 57.6 [397.1]] | 11.8 | 36.6 [40.2] |
| | LT | 63.7 [439.3] | 57.3 [395.1] | 8.8 | 29.1 [32.0] |
| | ST | 63.1 [435.1] | 56.6 [390.2] | 4.5 | 22.4 [24.6] |

**[0045]** A2 sample exhibits much higher strength and fracture toughness in the ST direction, which is an important critical direction for very thick gauge plate applications. In L and LT directions, A2 sample exhibits much higher strength at similar fracture toughness than sample B2 from the prior art. Specifically, in the L and LT directions, the strength was improved by about 18% and 14% respectively, at similar fracture toughness levels. In the ST direction, UTS and TYS were increased by about 18% and 13% respectively, while fracture toughness was increased by about 20%.

[**0046**] Additional advantages, features and modifications will readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to the specific details, and representative devices, shown and described herein. Accordingly, various modifications may be made without departing from the spirit or scope of the general inventive concept as defined by the appended claims and their equivalents.

[**0047**] All documents referred to herein are specifically incorporated herein by reference in their entireties.

[**0048**] As used herein and in the following claims, articles such as "the", "a" and "an" can connote the singular or plural.

**1**. An aluminum alloy having improved strength and fracture toughness comprising:

Cu: 2.5-5.5 wt. %

Li: 0.8-2.5 wt. %

Mg: 0.2-1 wt. %

Ag: 0.2-0.8 wt. %

Mn: 0.2-0.8 wt. %

Zr: up to 0.3 wt. % balance A1 and normal and/or inevitable elements and impurities.

**2**. An alloy according to claim 1, comprising 3 to 4 wt. % copper.

**3**. An alloy according to claim 1, comprising 0.8 to 1.8 wt. % lithium.

**4**. An alloy according to claim 1, comprising 0.8 to 1.5 wt. % lithium.

**5**. An alloy according to claim 3, comprising 0.8 to 1.2 wt. % lithium.

**6**. An alloy according to claim 1, comprising 0.3 to 0.5 wt. % magnesium.

**7**. An alloy according to claim 1, comprising 0.3 to 0.5 wt. % silver.

**8**. An alloy according to claim 1, comprising 0.3 to 0.5 wt. % manganese.

**9**. An alloy according to claim 1, comprising 0.05 to 0.15% zirconium.

**10**. An aluminum alloy having improved strength and fracture toughness comprising:

from about 2.5 to 5.5 wt. % copper, from about 0.8 to 2.5 wt. % lithium,

from about 0.2 to 1 wt. % magnesium, from about 0.2 to 0.8 wt. % silver, from about 0.2 to 0.8 wt. % manganese, optionally one or more elements selected from the group consisting of: (i) up to 0.3 wt. % Zr, (ii) up to 0.8 wt. % Cr, (iii) up to 0.12 wt. % Ti, (iv) up to 0.8 wt. % Sc, and (v) up to 0.2 wt. % V.

**11**. A rolled product comprising an aluminum alloy according to claim 10, with a thickness of at least about 3 inches, exhibiting in a solution heat-treated, quenched, stress-relieved and artificially aged condition, at least one set of properties selected from the group consisting of:

(a) UTS (L)>70 ksi (482.6 MPa) and KE (L)>34 ksNinch (37.4 MPaJm),

(b) TYS (L)>65 ksi (448.2 MPa) and $K_i$c (L)>34 ksi"Jinch (37.4 MParlm),

(c) UTS (LT)>70 ksi (482.6 MPa) and $K_i$c (L-T)>27 ksiAlinch (29.7 MPa-Jm),

(d) TYS (LT)>62 ksi (427.5 MPa) and $K_1$c (L-T)>26 ksi $^q$inch (28.6 MPaVm),

(e) UTS (ST)>70 ksi (482.6 MPa) and $K_i$c (S-T)>24 ksi-$^q$inch (26.4 MPaVm) and

(f) TYS (ST)>60 ksi (413.7 MPa) and $K_i$c (S-T)>23 ksiAlinch (25.3 MPajm).

**12**. A rolled product comprising an aluminum alloy according to claim 9, with a thickness of less than about 3 inches (76.2 mm), exhibiting in a solution heat-treated, quenched, stress-relieved and artificially aged condition at least one set of properties selected from the group consisting of:

(a) UTS (L)>76 ksi (524.0 MPa) and $K_{IC}$ (L)>35 ksi√inch (38.5 MPa√m),

(b) TYS (L)>71 ksi (489.5 MPa) and $K_{IC}$ (L)>35 ksi√inch (38.5 MPa√m),

(c) UTS (LT)>75 ksi 517.1 MPa) and $K_{IC}$ (L-T)>29 ksi√inch (31.9 MPa√m),

(d) TYS (LT)>68 ksi (468.8 MPa) and $K_{IC}$ (L-T)>29 ksi√inch (31.9 MPa√m),

(e) UTS (ST)>76 ksi (524.0 MPa) and $K_{IC}$ (S-T)>26 ksi√inch (28.6 MPa√m) and

(f) TYS (ST)>65 ksi (448.2 MPa) and $K_{IC}$ (S-T)>26 ksi√inch (28.6 MPa√m).

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