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(54) Method of improving fracture toughness in aluminium-lithium alloys

(57) An aluminum-lithium alloy is processed with controlled amounts of copper, lithium, manganese and zirconium to produce a product having improved fracture toughness in the short longitudinal (S-L) direction and acceptable strength in the short transverse (ST) direction.

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Description

Field of the Invention

[0001] The present invention is directed to a method of improving the fracture toughness in the short longitudinal direction in aluminum-lithium alloys and a product there from and, in particular, to a method which controls the levels of copper, manganese, lithium, and zirconium in the alloys to obtain the improved fracture toughness.

Background Art

[0002] It is well known that adding lithium as an alloying element to aluminum alloys results in beneficial mechanical properties.

[0003] Aluminum-lithium alloys exhibit improvements in stiffness and strength while reducing density. Consequently, these types or alloys have utility as structural materials in airplane and aerospace applications. Examples of known aluminum-lithium alloys include AA2097 and AA2197. The chemical compositions of these alloys are shown in Table 1 below.

[0004] Problems exist with aluminum-lithium alloys, particularly in thick plate of about 3 inches (76.2 mm) or greater, in terms of fracture toughness in the short longitudinal (S-L) direction.

[0005] Toughness values in this direction tend to be significantly lower than toughness values in other directions such as the longitudinal (L-T) direction or the long transverse (T-L) direction.

[0006] In view of the drawbacks in aluminum-lithium alloys with respect to fracture toughness, a need has developed to provide a method of improving the short longitudinal (S-L) direction fracture toughness for these types of alloys. In response to this need, the present invention provides both a method and a product therefrom which significantly increases the fracture toughness of aluminum-lithium alloys in the short longitudinal (S-L) direction, thereby improving their suitability for more commercial applications.

Summary of the Invention

[0007] A first object of the invention is to improve the fracture toughness in the short longitudinal (S-L) direction of aluminum-lithium alloys.

[0008] Another object of the invention is to provide a method of making an aluminum-lithium alloy having improved short longitudinal direction fracture toughness.

[0009] A still further object of the present invention is to utilize an aluminum-lithium alloy having controlled amounts of copper, lithium, manganese, zinc and zirconium to achieve fracture toughness improvements.

[0010] Yet another object of the present invention is to provide an aluminum-lithium alloy product having both improved fracture toughness in the short longitudinal (S-L) direction and acceptable strength in the short transverse direction.

[0011] Other objects and advantages of the present invention will become apparent as a description thereof proceeds.

[0012] In satisfaction of the foregoing objects and advantages, the present invention provides a method for improving the fracture toughness in the short longitudinal (S-L) direction in an aluminum-lithium alloy article comprising the steps of providing an aluminum alloy consisting essentially of, in weight percent all subsequent alloying levels are weight percent unless otherwise indicated): 2.5 to 4.0% copper, 0.8% to less than 1.3% lithium, 0.05 to 0.8% manganese, 0.04 to 0.18% zirconium, with the balance aluminum and inevitable impurities. The aluminum alloy can also include grain refining elements such as at least one of boron, titanium, vanadium, manganese, hafnium, scandium and chromium. Preferably, the aluminum alloy has only impurity levels of zinc so that it is essentially zinc-free, e.g., less than 0.05 weight percent zinc, more preferably less than or equal to 0.02%.

[0013] Preferably, the copper content is controlled between 2.7 and 3.0 weight percent. The lithium content is preferably controlled between about 1.2 to 1.28 weight percent to provide a low density product with good fracture toughness in the short longitudinal direction. Manganese is preferably between 0.30 and 0.32 weight percent, with zirconium being about 0.10 weight percent. It should be appreciated that the amounts of alloying elements, other than the amounts of lithium and copper, can be within the ranges described in the preceding paragraph.

[0014] In a modification of the composition described in the preceding paragraph, the lithium content ranges from about 0.8% to less than 1.2 and the copper content is between about 2.8 and 4%. This composition should provide even higher combined properties of fracture toughness and strength, with slightly higher density. In this composition range, additional theta' precipitate particles (Al_2Cu) would precipitate in addition to T1 precipitate particles (Al_2CuLi) at the grain boundaries. This would increase the combined properties of strength and fracture toughness in the short longitudinal direction.

[0015] Magnesium can be added if desired, in an amount up to 0.35% weight percent, preferably, up to 0.25 weight percent. Small amounts of magnesium may be beneficial in terms of strength and lowering of density. However, excessive amounts may create susceptibility to stress corrosion cracking and do not provide further benefits in terms of strength and density reduction.

[0016] The aluminum alloy is cast into an ingot and homogenized for a select period of time. The homogenized ingot is then hot worked into a shape such as a plate and solution heat treated for a select period of time. The solution heat treated shape is then quenched, preferably in water, cold worked, preferably by stretching, and aged for a select period of time. With this processing, the cold worked (stretched) and aged shape exhibits equivalent strengths but higher fracture toughness in the short longitudinal (S-L) direction than similar aluminum alloys having lithium contents greater than 1.38.

[0017] The homogenization and solution heat treating temperatures can range between about 9000 and 1030°F (482 to 554°C), preferably between about 930°F (499°C) and 1000°F (538°C). More preferably, homogenization temperatures will range between about 940°F (505°C) to 975°F (524°C), and solution heat treating temperatures will range between about 975°F (524°C) to 1000°F (538°C) . The preferred temperature often depends on the particular alloy composition as will be understood by one skilled in the art. Homogenization times can be about 8 to 48 hours, preferably about 24 to about 36 hours. Solution heat treating times can range from about 1 to 10 hours, preferably about 1 hour to 6 hours, more preferably about 2 hours, once the metal reaches a desired temperature. The plate may be artificially aged without any cold work. However, it is preferred to provide between about 4 and 8 cold work, preferably by stretching. The plate is preferably artificially aged between about 300 and 3500F (149 to 177°C) for between about 4 and about 48 hours, preferably between about 12 and about 36 hours, with the aging time being a function of the aging temperature.

[0018] Using the inventive processing, an aluminum-lithium alloy article is made having vastly improved fracture toughness in the short longitudinal (S-L) direction. The fracture toughness value in the short longitudinal (S-L) direction is at least about 689 of the fracture toughness in the long transverse (T-L) direction. While exhibiting improved fracture toughness in the short longitudinal (S-L) direction, the inventive aluminum-lithium alloy articles have tensile yield strengths exceeding about 54 KSI.

Brief Description of the Drawings

[0019] Reference is now made to the drawings of the invention wnerein:

Figure 1 compares the invention to the prior art in terms of tensile yield strength in the short transverse direction and fracture toughness in the short longitudinal (S-L) direction;

Figure 2 compares prior art alloy products and the invention alloy products with respect to lithium content and fracture toughness in the short longitudinal (S-L) direction; and

Figure 3 compares the prior art alloy products and the invention alloy products with respect to copper content and fracture toughness in the short longitudinal (S-L) direction.

Description of the Preferred Embodiment

[0020] The present invention solves a significant problem in the field of aluminum-lithium materials for structural applications such as those found in the aerospace and airplane industry. That is, by controlling the compositional amounts of copper, lithium, manganese and zirconium in these types of alloys, acceptable fracture toughness in the short longitudinal (S-L) direction with acceptable strength in the short transverse (ST) direction is obtained. This unexpected improvement in fracture toughness in the S-L direction permits the use of these types of alloys in a wide variety of structural applications requiring low weight, high strength and stiffness, and good fracture toughness.

[0021] According to the present invention, the alloy elements of copper, lithium, manganese and zirconium are controlled in the following ranges to achieve the improvements in fracture toughness: about 2.5 to 4.0 weight percent copper, about 0.8 to less than about 1.2 or 1.3 weight percent lithium, about 0.05 to 0.8 weight percent manganese, about 0.04 to 0.16 weight percent zirconium, with the balance aluminum and inevitable impurities. One or more grain refining elements can also be added to the aluminum-lithium composition described above. The grain refining elements can be selected from the group consisting of titanium in an amount up to 0.2 weight percent, boron in an amount of up to 0.2 weight percent, vanadium in an amount of up to 0.2 weight percent, manganese in an amount of up to 0.8 weight percent, hafnium in an amount up to 0.2 weight percent, scandium in an amount up to 0.5 weight percent, and chromium in an amount up to 0.3 weight percent. Preferably the aluminum is free of zinc. In other words, zinc is present only as an impurity and at levels less than 0.05 weight percent. It is believed that zinc in levels greater than such impurity level adversely affects the mechanical properties of these types of aluminum-lithium alloys.

[0022] The copper content should be kept higher than 2.5 weight percent to achieve high strength but less than 4.0

weight percent to avoid undissolved particles during solution heat treatment.

[0023] Higher levels of copper are preferred due to the lower levels of lithium in the alloy.

[0024] The lithium content should be kept higher than 0.8 weight percent to achieve good strength and low density but less than 1.3 weight percent to avoid a loss of fracture toughness in the short longitudinal (S-L) direction. The manganese content should be kept below 0.8 weight percent to avoid large non-dissolvable particles which would be detrimental to fracture toughness. The manganese should be higher than 0.05 weight percent to control grain size and homogenous slip behavior during plastic deformation processing.

[0025] More preferably, the lithium content should be controlled between 1.2 and to less than 1.3 weight percent. Still more preferably, in one embodiment, the lithium content is controlled to less than 1.2 weight percent. The manganese is more preferably between 0.3 and 0.32 weight percent with the copper level ranging between about 2.7 and 3.0 weight percent.

[0026] Magnesium can be added if desired, in an amount preferably up to 0.35% weight percent, preferably, up to 0.25 weight percent. Small amount of magnesium may be beneficial in terms of strength and lowering of density. However, excessive amounts may create susceptibility to stress corrosion cracking and do not provide further benefits in terms of strength and density reduction.

[0027] In conjunction with specifying the alloy composition in the aluminum-lithium alloy composition above, the alloy is processed by the steps of casting, homogenizing, hot working (for instance, by rolling, forging, extruding and combinations thereof), solution heat treating, quenching, cold working (for instance by stretching) and aging to form an aluminum-lithium article having the improvements in fracture toughness in the S-L direction.

[0028] As part of this processing, the aluminum-lithium alloy described above is cast into an ingot, billet or other shape to provide suitable stock for the subsequent processing operations. Once the shape is cast, it can be stress-relieved as is known in the art prior to homogenization. The cast shape is then homogenized at temperatures in the range of 9300F to 1,0300F, 4990C to 55440C, for a sufficient period of time to dissolve the soluble elements and homogenize the internal structure of the metal. A preferred homogenization residence time is in the range of 1 to 36 hours, while longer times do not normally adversely affect the article. The homogenization can be conducted at one temperature or in multiple steps utilizing several temperatures.

[0029] After homogenization, the cast shape is then hot worked to produce stock such as sheet, plate, extrusions, or other stock material depending on the desired end use of the aluminum-lithium alloy article. For example, an ingot having a rectangularly shaped cross section could be hot worked into a plate form. Since this hot working step is conventional in the art, a further description thereof is not deemed necessary for understanding of the invention.

[0030] Following the hot working step, the hot worked shape is then solution heat treated and quenched. Preferably, the hot worked shape is solution heat treated between 930° to 1030°F (499° to 554°C) at a time from less than an hour to up to several hours. This solution heat treated shape is preferably rapidly quenched, e.g. quenched in ambient temperature water, to prevent or minimize uncontrolled precipitation of strengthening phases in the alloy.

[0031] The rapid quenching can also include a subsequent air cooling step, if desired.

[0032] The quenched shape is then preferably stretched up to 8% and artificially aged in the temperature range of 150° to 400°F (66° to 204°C) for sufficient time to further increase the yield strength, e.g., up to 100 hours, depending on the temperature, for instance, 24 hours at 300°F (149°C) . The stretched and aged shape is then ready for use in any application, particularly an aerospace or airplane application. Alternatively, prior to aging, the shape may be formed into an article and then aged.

[0033] In order to demonstrate the unexpected improvements associated with the present invention, a comparison was made between properties of articles made from aluminum-lithium alloys of the prior art and articles made from aluminum-lithium alloys according to the invention. In this comparison, four prior art chemistries were selected along with four chemistries according to the invention. An aluminum alloy melt was made from each of the eight chemistries and processed by casting, homogenizing, solution heat treating, quenching, stretching and aging to produce an aluminum-lithium alloy article or product. The aluminum-lithium alloy articles were then subjected to tensile and fracture toughness testing to compare the mechanical properties of the prior art chemistries to those corresponding to the instant invention.

[0034] The following details the processing used and test methods to compare the mechanical properties of the prior art and inventive aluminum-lithium alloy articles. In the comparison, the prior art articles are designated as Examples 1-4, and the articles of the invention are designated as Examples 5-8.

[0035] It should be understood that the processing variables and chemistries disclosed in Examples 5-8 are more preferred embodiments of the invention.

Table 1

	Si	Fe	Cu	Mn	Mg	Zn	Zr	Ti	Li
AA2097	0.12	0.15	2.5-3.1	0.10-0.6	0.35	0.35	0.08-0.16	0.15	1.2-1.8
AA2197	0.10	0.10	2.5-3.1	0.10-0.5	0.25	0.05	0.08-0.15	0.12	1.3-1.7

Table 1 Notes

1. Chemical compositions are expressed in a weight percent maximum unless shown as a range.
2. In addition to the listed elements, each alloy may contain other elements, with the maximum amount of each other element not exceeding 0.05 wt. % and thetotal of other elements not exceeding 0.15 wt. %.

Example 1

[0036] An aluminum alloy consisting of, in weight percent, 2.84 Cu-1.36 Li-.32 Mn.-.1 Zr, the balance aluminum and impurities, was cast into an ingot with a cross section of 16" (406.4 mm) and 45" (1143 mm) wide. The ingot was homogenized at 950°F (510°C) for 36 hours, then hot worked to 4" (101.6 mm) thick plate. The plate was then solution heat treated in a heat treating furnace at a temperature of 990°F (532°C) for 2 hours and then quenched in water. The plate was then stretched by 6% in the longitudinal direction at room temperature. For artificial aging, the stretched samples were aged in an oven at 320°F (160°C)for 24 hours. Tensile properties were determined at the T/4 plane in accordance with ASTM B-557. Tensile tests in the longitudinal direction and the long transverse direction used round tensile specimens with .5" (12.7 mm) diameter and 1" (25.4 mm) gauge length. Tensile tests in the short transverse direction were conducted with round tensile specimens with .160" (4.1 mm) diameter and .5" (12.7 mm) gauge length. Fracture toughness was determined at the T/4 plane by ASTM standard practice E266 using W=1.5" (38.1 mm) Compact Tension specimens for the short longitudinal direction and W=2" (50.8 mm) Compact Tension specimens for the L-T and T-L directions. The results of these tests are listed in Table 2.

TABLE 2

Chemistry (weight %)

Cu	Li	Mn	Zr
2.84	1.36	.32	.1

Mechanical Properties

Test Direction	Ultimate Strength (KSI)*	Yield stress (KSI)	Elongation %	Test Direction	Fracture Toughness KSI √in**
ST	62.7	54.3	3.6	S-L	18.4
LT	67.2	60.0	6.5	T-L	28
L	67.7	62.1	10	L-T	32

* 1 KSI = 6.894757 MPa

** KSI √in = 1.0988434 MPa √m

Example 2

[0037] An aluminum alloy consisting of, in weight percent, 2.71 Cu-1.37 Li-.32 Mn.-.1 Zr, the balance aluminum and impurities, was cast into an ingot with a cross section of 16" (406.4 mm) and 45" (1143 mm) wide. The ingot was homogenized at 950°F (5100C) for 36 hours, then hot worked to 4" (101.6 mm) thick plate. The plate was then solution heat treated in a heat treating furnace at a temperature of 990°F (532°C) for 2 hours and then quenched in water. The plate was then stretched by 6% in the longitudinal direction at room temperature. For artificial aging, the stretched samples were aged in an oven at 320°F (160°C)for 24 hours. Tensile properties were determined at the T/4 plane in accordance with ASTM B-557. Tensile tests in the longitudinal direction and long transverse direction used round tensile specimens with .5" (12.7 mm) diameter and 1" (25.4 mm) gauge length. Tensile tests in the short transverse direction were conducted with round tensile specimens with .160" (4.1 mm) diameter and .5" (12.7 mm) gauge length. Fracture toughness was determined at the T/4 plane by ASTM standard practice E266 using W=1.5" (38.1 mm) Compact Tension specimens for the short longitudinal (S-L) direction and W=2" (50.8 mm) Compact Tension specimens for the L-T and T-L directions. The results of these tests are listed in Table 3.

TABLE 3

Chemistry (weight %)

Cu	Li	Mn	Zr
2.71	1.37	.32	.1

Mechanical Properties

Test Direction	Ultimate Strength (KSI)*	Yield stress (KSI)	Elongation %	Test Direction	Fracture Toughness KSI √in**
ST	66.8	59.8	4.7	S-L	15.8
LT	68.1	61.9	6.5	T-L	29.1
L	70.4	65.8	9.5	L-T	32.7

* 1 KSI = 6.894757 MPa

** KSI √in = 1.0988434 MPa √m

Example 3

[0038] An aluminum alloy consisting of, in weight percent, 2.77 Cu-1.33 Li-.32 Mn.-. 11 Zr, the balance aluminum and impurities, was cast into an ingot with a cross section of 16" (406.4 mm) and 45" (1143 mm) wide. The ingot was homogenized at 950°F (510°C) for 36 hours, then hot worked to 4" (101.6 mm) thick plate. The plate was then solution heat treated in a heat treating furnace at a temperature of 990°F (532°C) for 2 hours and then quenched in water. The plate was then stretched by 6% in the longitudinal direction at room temperature. For artificial aging, the stretched samples were aged in an oven at 320°F (160°C)for 24 hours. Tensile properties were determined at the T/4 plane in accordance with ASTM 5-557. Tensile tests in the longitudinal direction and the long transverse direction used round tensile specimens with .5" (12.7 mm) diameter and 1" (25.4 mm) gauge length. Tensile tests in short transverse direction were conducted with round tensile specimens with .160" (4.1 mm) diameter and .5" (12.7 mm) gauge length. Fracture toughness was determined at the T/4 plane by ASTM standard practice E266 using W=1.5" (38.1 mm) Compact Tension specimens for the short longitudinal direction and W=2" (50.8 mm) Compact Tension specimens for the L-T and T-L directions. The results of these tests are listed in Table 4.

TABLE 4

Chemistry (weight %)

Cu	Li	Mn	Zr
2.77	1.33	.32	.11

Mechanical Properties

Test Direction	Ultimate Strength (KSI)*	Yield stress (KSI)	Elongation %	Test Direction	Fracture Toughness KSI √in**
ST	65.6	56.7	3.5	S-L	15.5
LT	68.7	62.0	6.0	T-L	26.8
L	70.7	65.5	11	L-T	28.1

* 1 KSI = 6.894757 MPa

** KSI √in = 1.0988434 MPa √m

Example 4

[0039] An aluminum alloy consisting of, in weight percent, 2.89 Cu-1.36 Li-.32 Mn.-0.1 Zr, the balance aluminum and impurities, was cast into an ingot with a cross section of 16" (406.4 mm) and 45" (1143 mm) wide. The ingot was homogenized at 950°F (5100C) for 36 hours, then hot worked to 4" (101.6 mm) thick plate. The plate was then solution heat treated in a heat treating furnace at a temperature of 990°F (532°C) for 2 hours and then quenched in water. The plate was then stretched by 6% in the longitudinal direction at room temperature. For artificial aging, the stretched samples were aged in an oven at 320°F (160°C)for 24 hours. Tensile properties were determined at the T/4 plane in accordance with ASTM B-557. Tensile tests in the longitudinal direction and the long transverse direction used round tensile specimens with .5" (12.7 mm) diameter and 1" (25.4 mm) gauge length. Tensile tests in the short transverse direction were conducted with round tensile specimens with .160" (4.1 mm) diameter and .5" (12.7 mm) gauge length. Fracture toughness was determined at the T/4 plane by ASTM standard practice E266 using W=1.5" (38.1 mm) Compact Tension specimens for the short longitudinal (S-L) direction and W=2" (50.8 mm) Compact Tension specimens for the L-T and T-L directions. The results of these tests are listed in Table 5.

TABLE 5

Chemistry (weight %)

Cu	Li	Mn	Zr
2.89	1.36	.32	.10

Mechanical Properties

Test Direction	Ultimate Strength (KSI)*	Yield stress (KSI)	Elongation %	Test Direction	Fracture Toughness KSI √in**
ST	63.6	56.3	2.1	S-L	20.4
LT	64.7	57.2	8.0	T-L	30.8
L	76.5	60.7	10	L-T	32.2

* 1 KSI = 6.894757 MPa

** KSI √in = 1.0988434 MPa √m

Example 5

[0040] An aluminum alloy consisting of, in weight percent, 2.78 Cu-1.21 Li-.31 Mn.-0.1 Zr, the balance aluminum and impurities, was cast into an ingot with a cross section of 16" (406.4 mm) and 45" (1143 mm) wide. The ingot was homogenized at 950°F (510°C) for 36 hours, then hot worked to 4" (101.6 mm) thick plate. The plate was then solution heat treated in a heat treating furnace at a temperature of 990°F (532°C) for 2 hours and then quenched in water. The plate was then stretched by 8% in the longitudinal direction at room temperature. For artificial aging, the stretched samples were aged in an oven at 320°F (160°C)for 24 hours. Tensile properties were determined at the T/4 plane in accordance with ASTM B-557. Tensile tests in the longitudinal direction and the long transverse direction used round tensile specimens with .5" (12.7 mm) diameter and 1" (25.4 mm) gauge length. Tensile tests in the short transverse direction were conducted with round tensile specimens with .160" (4.1 mm) diameter and .5" (12.7 mm) gauge length. Fracture toughness was determined at the T/4 plane by ASTM standard practice E26 using W=1.5" (38.1 mm) Compact Tension specimens for the short longitudinal (S-L) direction and W=2" (50.8 mm) Compact Tension specimens for the L-T and T-L directions. The results of these tests are listed in Table 6.

TABLE 6

Chemistry (weight %)			
Cu	Li	Mn	Zr
2.78	1.21	.31	.1

Mechanical Properties

Test Direction	Ultimate Strength (KSI)*	Yield stress (KSI)	Elongation %	Test Direction	Fracture Toughness KSI √in**
ST	62.5	54.7	3.6	S-L	26.6
LT	65.1	58	8.5	T-L	31.5
L	64.4	59.1	11.5	L-T	37.5

* 1 KSI = 6.894757 MPa

** KSI √in = 1.0988434 MPa √m

Example 6

[0041] An aluminum alloy consisting of, in weight percent, 2.86 Cu-1.28 Li-.3 Mn.-0.1 Zr, the balance aluminum and impurities, was cast into an ingot with a cross section of 16" (406.4 mm) and 45" (1143 mm) wide. The ingot was homogenized at 950°F (510°C) for 36 hours, then hot worked to 4" (101.6 mm) thick plate. The plate was then solution heat treated in a heat treating furnace at a temperature of 990°F (532°C) for 2 hours and then quenched in water. The plate was then stretched by 6% in the longitudinal direction at room temperature. For artificial aging, the stretched samples were aged in an oven at 320°F (160°C) for 24 hours. Tensile properties were determined at the T/4 plane in accordance with ASTM B-557. Tensile tests in the longitudinal direction and the long transverse direction used round tensile specimens with .5" (12.7 mm) diameter and 1" (25.4 mm) gauge length. Tensile tests in the short transverse direction were conducted with round tensile specimens with .160" (4.1 mm) diameter and .5" (12.7 mm) gauge length. Fracture toughness was determined at the T/4 plane by ASTM standard practice E266 using W=1.5" (38.1 mm) Compact Tension specimens for the short longitudinal (S-L) direction and W=2" (50.8 mm) Compact Tension specimens for the L-T and the T-L directions. The results of these tests are listed in Table 7.

TABLE 7

Chemistry (weight %)

Cu	Li	Mn	Zr
2.86	1.28	.30	.10

Mechanical Properties

Test Direction	Ultimate Strength (KSI)*	Yield stress (KSI)	Elongation %	Test Direction	Fracture Toughness KSI √in**
ST	64	57.3	4.1	S-L	26.3
LT	66.4	59.4	7.5	T-L	34.2
L	66.4	61.3	9.5	L-T	40.1

* 1 KSI = 6.894757 MPa

** KSI √in = 1.0988434 MPa √m

Example 7

[0042] An aluminum alloy consisting of, in weight percent, 2.73 Cu-1.28 Li-.3 Mn.-0.1 Zr, the balance aluminum and impurities, was cast into an ingot with a cross section of 16" (406.4 mm) and 45" (1143 mm) wide. The ingot was homogenized at 950%F (510°C) for 36 hours, then hot worked to 4" (101.6 mm) thick plate. The plate was then solution heat treated in a heat treating furnace at a temperature of 990°F (532°C) for 2 hours and then quenched in water. The plate was then stretched by 6% in the longitudinal direction at room temperature. For artificial aging, the stretched samples were aged in an oven at 320°F (160°C)for 24 hours. Tensile properties were determined at the T/4 plane in accordance with ASTM B-557. Tensile tests in the longitudinal direction and the long transverse direction used round tensile specimens with .5" (12.7 mm) diameter and 1" (25.4 mm) gauge length. Tensile tests in the short transverse direction were conducted with round tensile specimens with .160" (4.1 mm) diameter and .5" (12.7 mm) gauge length. Fracture toughness was determined at the T/4 plane by ASTM standard practice E266 using W=1.5" (38.1 mm) Compact Tension specimens for the short longitudinal (s-L) direction and W=2" (50.8 mm) Compact Tension specimens for the L-T and the T-L directions. The results of these tests are listed in Table 8.

TABLE 8

Chemistry (weight %)

Cu	Li	Mn	Zr
2.73	1.28	.30	.1

Mechanical Properties

Test Direction	Ultimate Strength (KSI)*	Yield stress (KSI)	Elongation %	Test Direction	Fracture Toughness KSI √in**
ST	64.4	55.9	3.6	S-L	22.7
LT	65.4	58.8	7.5	T-L	33.1
L	64	59	12	L-T	38.5

* 1 KSI = 6.894757 MPa

** KSI √in = 1.0988434 MPa √m

Example 8

[0043] An aluminum alloy consisting of, in weight percent, 2.83 Cu-1.26 Li-.32 Mn.-0.11 Zr, the balance aluminum and impurities, was cast into an ingot with a cross section of 16" (406.4 mm) and 45" (1143 mm) wide. The ingot was homogenized at 950°F (510°C) for 36 hours, then hot worked to 4" (101.6 mm) thick plate. The plate was then solution heat treated in a heat treating furnace at a temperature of 990°F (532°C) for 2 hours and then quenched in water. The plate was then stretched by 6% in the longitudinal direction at room temperature. For artificial aging, the stretched samples were aged in an oven at 320°F (160°C)for 24 hours. Tensile properties were determined at the T/4 plane in accordance with ASTM B-557. Tensile tests in the longitudinal direction and the long transverse direction used round tensile specimens with .5" (12.7 mm) diameter and 1" (25.4 mm) gauge length. Tensile tests in the short transverse direction were conducted with round tensile specimens with .160" (4.1 mm) diameter and .5" (12.7 mm) gauge length. Fracture toughness was determined at the T/4 plane by ASTM standard practice E266 using W=1.5" (38.1 mm) Compact Tension specimens for the short longitudinal (S-L) direction and W=2" (50.8 mm) Compact Tension specimens for the L-T and the T-L directions. The results of these tests are listed in Table 9.

TABLE 9

Chemistry (weight %)			
Cu	Li	Mn	Zr
2.83	1.26	.32	.11

Mechanical Properties

Test Direction	Ultimate Strength (KSI)*	Yield stress (KSI)	Elongation %	Test Direction	Fracture Toughness KSI √in**
ST	63.9	55.9	3.6	S-L	22.7
LT	65.4	58.8	7.5	T-L	33.1
L	64.0	59	12	L-T	38.5

* 1 KSI = 6.894757 MPa

** KSI √in = 1.0988434 MPa √m

[0044] The advantage of the present invention is shown in Figure 1 which correlates the fracture toughness values in Tables 2-9 in the S-L direction with tensile yield strengths in the S-T direction. As is evident from Figure 1, no compromise is made in the tensile yield strengths between the prior art examples and the examples of the invention. More specifically, the prior art tensile yield strength values range from just above 54 KSI to almost 60 KSI. In comparison, the tensile yield strengths of the examples according to the invention range from just below 55 KSI to just above 57 KSI. Figure 1 demonstrates that the articles made of the present invention provide significantly improved fracture toughness in the S-L direction while maintaining acceptable strength levels in the S-T direction.

[0045] Figure 2 illustrates the unexpected improvements in fracture toughness in the S-L direction over the prior art. The values depicted in Figure 2 demonstrate that the fracture toughness in the S-L direction for Examples 5-8 is vastly superior to that shown for Examples 1-4. This improvement, which relates to lithium content, is quite unexpected in view of the prior art.

[0046] Figure 3 emphasizes the fact that the improvements in fracture toughness are related to the lithium content of the alloys. Figure 3 demonstrates that the fracture toughness does not vary widely with respect to copper content. For Examples 5-8, the fracture toughness appears to remain relatively the same with increasing or decreasing amounts of copper. Similarly, the fracture toughness of Examples 1-4 does not vary widely with increasing or decreasing copper content.

[0047] Referring again to Figure 2, it is believed that the lithium content can be as low as 0.8 weight percent while still giving improvements in fracture toughness and maintaining the acceptable strength in the short transverse direction. It is further believed that the same results are obtainable when practicing the inventive processing in accordance with the broad processing variable ranges disclosed above.

[0048] Accordingly, an invention has been disclosed in terms of preferred embodiments thereof which fulfill each and every one of the objects of the present invention as set forth above and provides a new and improved method for improving the short longitudinal direction fracture toughness of aluminum-lithium alloys.

[0049] Various changes, modifications and alterations from the teachings of the present invention may be contemplated by those skilled in the art without departing from the intended spirit and scope thereof. Accordingly, it is intended that the present invention only be limited by the terms of the appended claims.

Claims

1. A method of improving the fracture toughness in a short longitudinal direction of an aluminum-lithium alloy article comprising the steps of:

a) providing an aluminum alloy consisting essentially of, in weight percent:

2.5 to 4.0% copper,
0.8 to less than 1.3% lithium,
0.05 to 0.8% manganese,
up to 0.25% magnesium,
0.04 to 0.18% zirconium,
optionally one or more grain refining elements selected from the group consisting of up to 0.2 % titanium, up to 0.2 % boron, up to 0.2 % vanadium, up to 0.8 % manganese, up to 0.2 % hafnium, up to 0.5 % scandium, and up to 0.3 % chromium,

the balance aluminum and inevitable impurities;
b) casting the aluminum alloy into an ingot;
c) homogenizing the ingot at between 930° and 1000°F (499 to 538 °C);
d) hot working the homogenized ingot into a hot worked shape;
e) solution heat treating the hot worked shape at between 975° and 1000°F (524 to 538°C);
f) quenching the solution heat treated shape; and
g) cold working and aging the quenched shape.

2. The method of claim 1 wherein the shape is stretched between 4 and 8% and then aged between 150 and 400 °F (66 to 204 °C), and preferably between about 300 and 350°F (149 to 177°C).

3. The method of claims 1 or 2 wherein the lithium content is less than 1.2% by weight.

4. The method of claim 1, wherein the lithium content ranges between about 1.2 and 1.28%.

5. The method of claims 1 or 2 wherein the copper content is between 2.7 and 3.0 %.

6. The method of claim 1 wherein the lithium content is less than 1.2% by weight and the copper content is more than 2.8% by weight.

7. The method of claim 3 wherein zirconium is between 0.04 and 0.16 %.

8. The method of claims 1 to 7 wherein the aluminum alloy is essentially zinc free.

9. The method of claim 1 wherein manganese is higher than 0.05 %.

10. The method of claims 1 to 9, wherein said aluminum-lithium article is a thick plate.

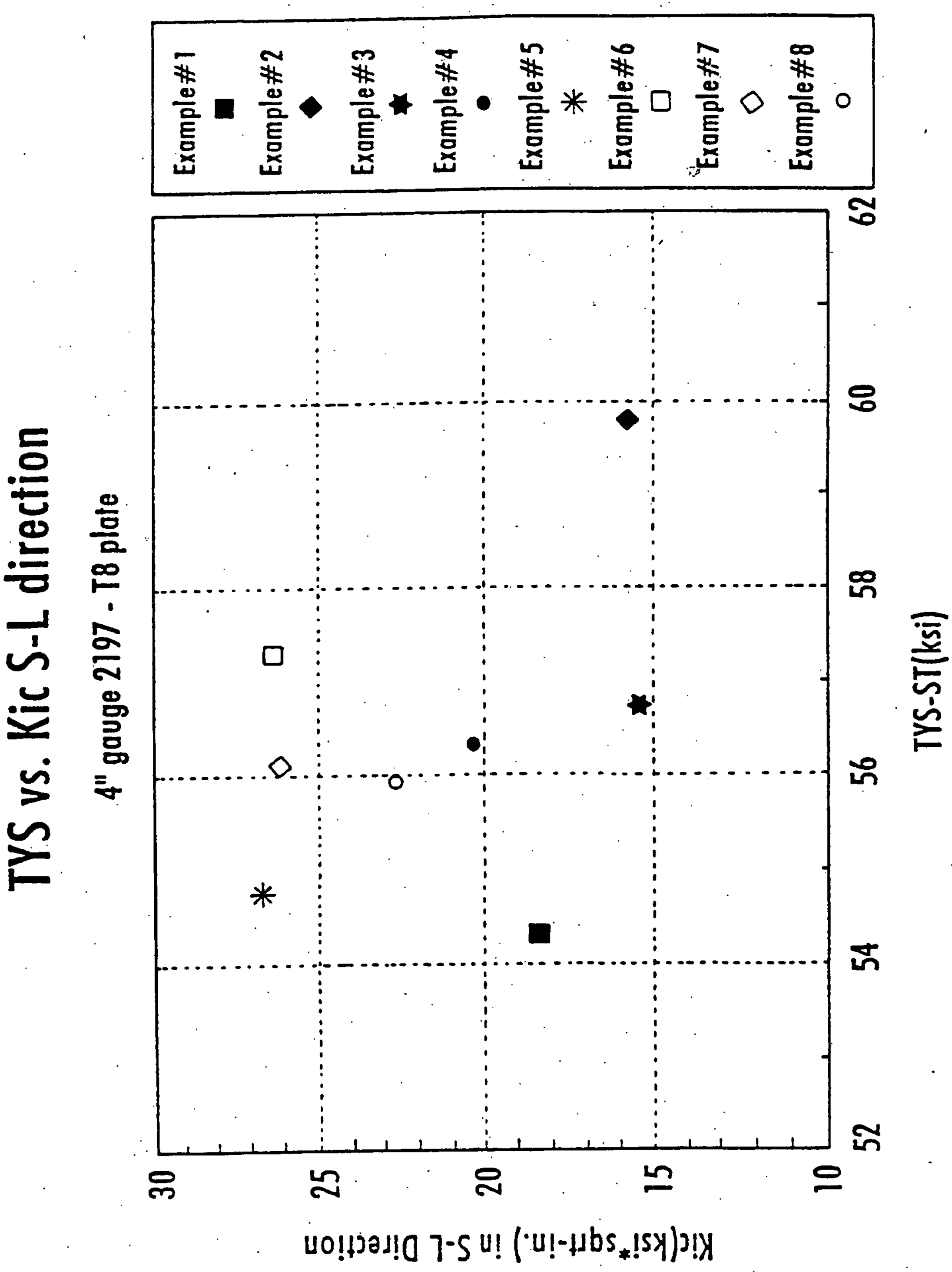
11. The method of claim 1 wherein the fracture toughness of the plate in the short longitudinal (S-L) direction is at least about 68.5% of the fracture toughness of the plate in the long transverse (T-L) direction.

12. The product made by the method of claims 1 to 11.

12. The made by the method of claim 1 having a fracture toughness of at least 21.0 ksi√in (23 MPa√m) the short longitudinal direction.

13. The product made by the method of claim 1 having a fracture toughness of at least 21.0 ksi√in (23 MPa√m) in the short longitudinal direction and a tensile yield strength of at least 54.0 ksi (372.3 MPa) in the short transverse direction.

14. The product of claim 13 wherein the fracture toughness is at least 22.7 ksi√in (24.94 MPa√m) and the tensile yield strength is at least 54.7 ksi (377 MPa).



TYS vs. Kic S-L direction
4" gauge 2197 - T8 plate
Kic(ksi*sqrt-in.) in S-L Direction
30
25
20
15
10
52
54
56
58
60
62
TYS-ST(ksi)
Example#1
Example#2
Example#3
Example#4
Example#5
Example#6
Example#7
Example#8

Figure 1

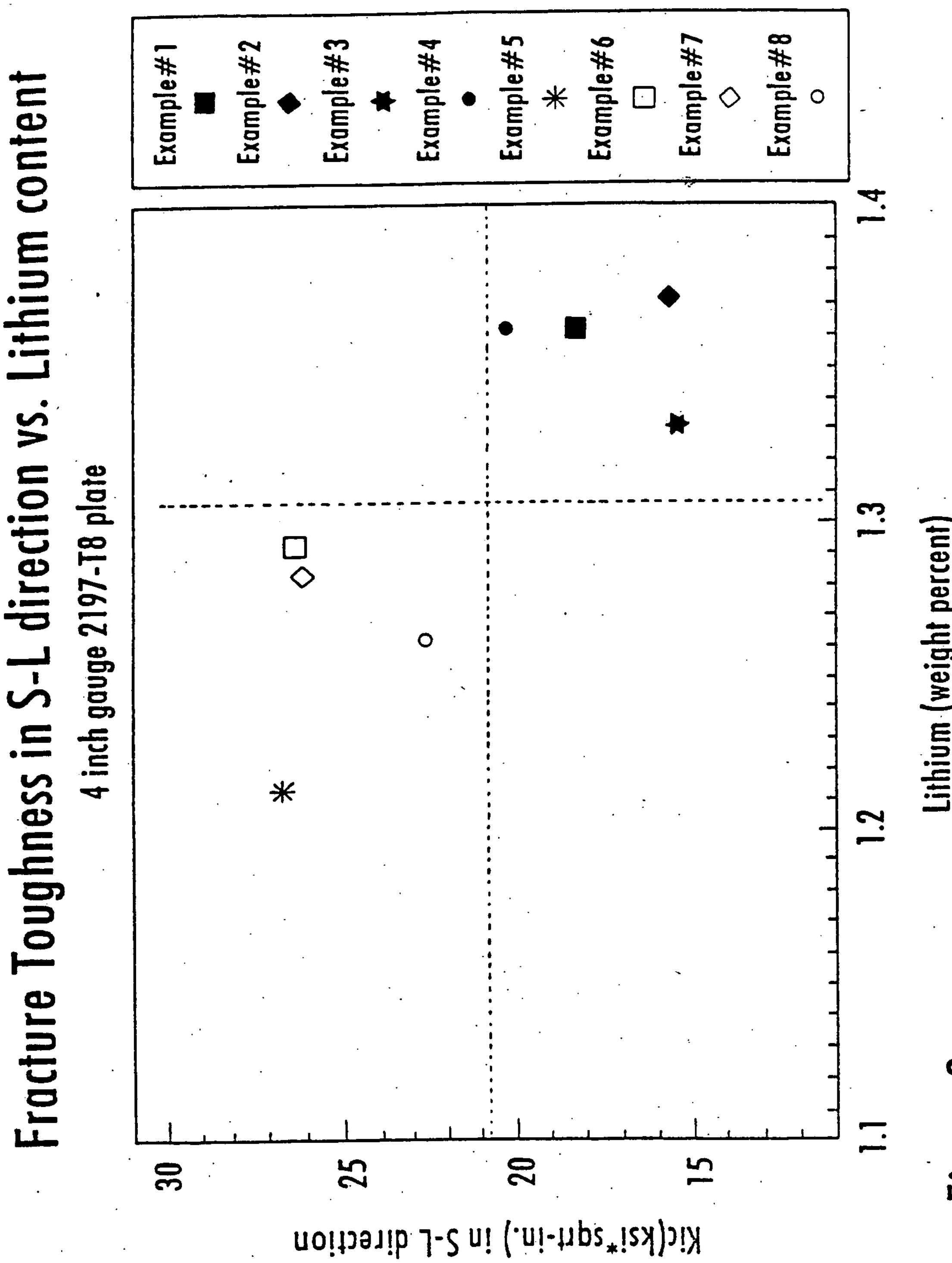

Fracture Toughness in S-L direction vs. Lithium content
4 inch gauge 2197-T8 plate
Kic(ksi*sqrt-in.) in S-L direction
30
25
20
15
1.1
1.2
1.3
1.4
Lithium (weight percent)
Example#1
Example#2
Example#3
Example#4
Example#5
Example#6
Example#7
Example#8

Figure 2

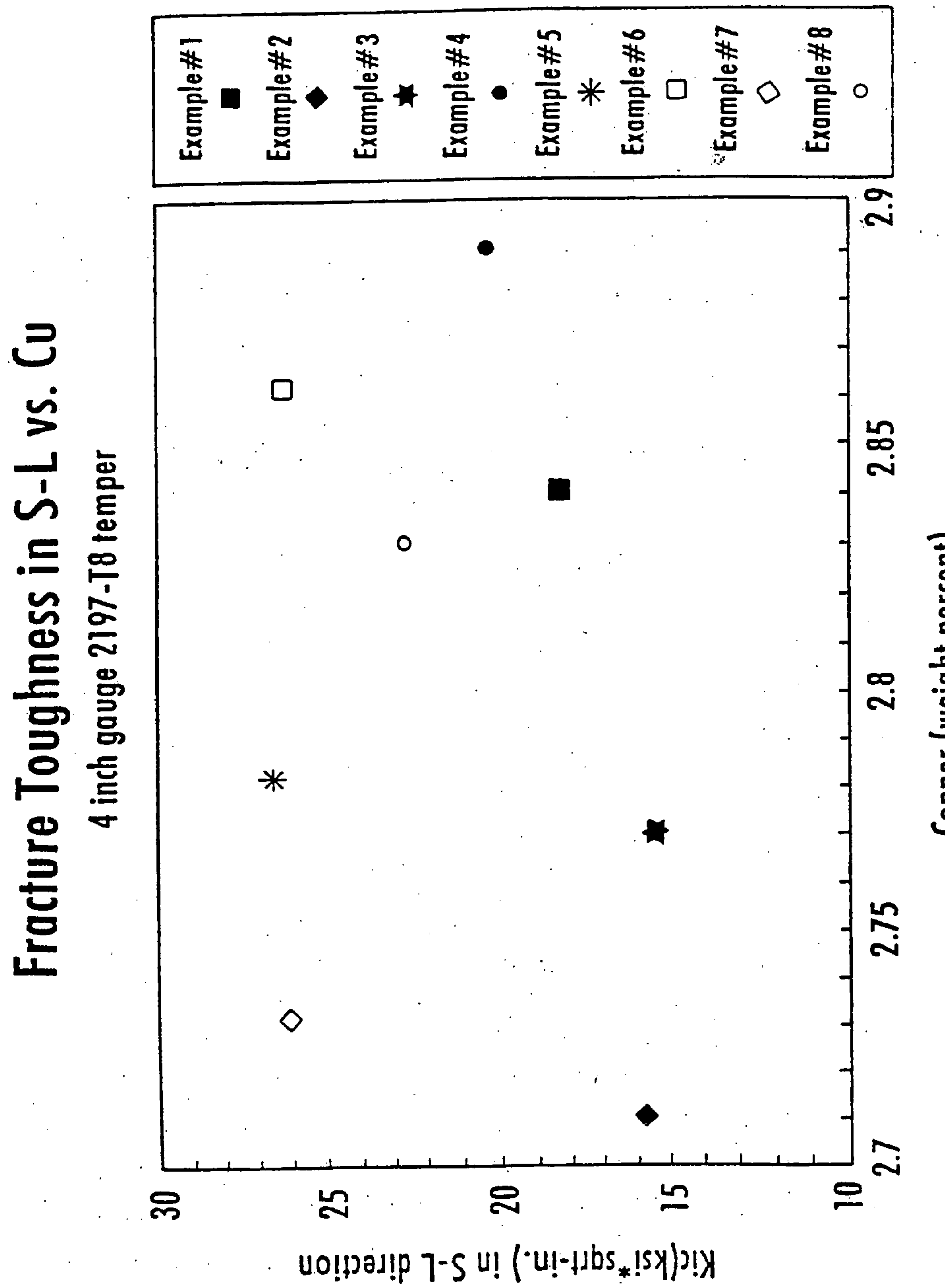

Fracture Toughness in S-L vs. Cu
4 inch gauge 2197-T8 temper
Kic(ksi*sqrt-in.) in S-L direction
30
25
20
15
10
2.7
2.75
2.8
2.85
2.9
Copper (weight percent)
Example#1
Example#2
Example#3
Example#4
Example#5
Example#6
Example#7
Example#8

Figure 3