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(54) **Heat treatable L12 aluminum alloys**

Hitzebehandelbare L12-Aluminiumlegierungen

Alliages d'aluminium L12 traitables thermiquement

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(56) References cited:  
**EP-A1- 1 439 239 EP-A1- 2 110 452**  
**WO-A1-01/12868 WO-A1-03/052154**  
**FR-A1- 2 843 754 JP-A- 9 104 940**

**US-A- 5 055 257 US-A- 5 624 632**  
**US-A1- 2005 013 725 US-B1- 6 258 318**

- **LITYNSKA LIDIA ET AL: "Experimental and theoretical characterization of Al<sub>3</sub>Sc precipitates in Al-Mg-Si-Cu-Sc-Zr alloys" ZEITSCHRIFT FÜR METALLKUNDE, CARL HANSER, MUNICH, DE, vol. 97, no. 3, 1 January 2006 (2006-01-01), pages 321-324, XP009120841 ISSN: 0044-3093**
- **LITYNSKA-DOBRZYNSKA ET AL: "Precipitation of phases in Al-Mg-Si-Cu alloy with Sc and Zr additions during heat treatment" DIFFUSION AND DEFECT DATA. SOLID STATE DATA. PART B, SOLID STATE PHENOMENA, VADUZ, LI, vol. 130, no. Applied crystallography XX, 1 January 2007 (2007-01-01), pages 163-166, XP009120850 ISSN: 1012-0394**
- **CABIBBO MET AL: "A TEM study of the combined effect of severe plastic deformation and (Zr), (Sc+Zr)-containing dispersoids on an Al-Mg-Si alloy" JOURNAL OF MATERIALS SCIENCE, KLUWER ACADEMIC PUBLISHERS, BO LNKD-DOI:10.1007/S10853-006-0306-2, vol. 41, no. 16, 6 June 2006 (2006-06-06), pages 5329-5338, XP019399254 ISSN: 1573-4803**
- **LITYNSKA-DOBRZYNSKA, L.: "Effect of heat treatment on the sequence of phases formation in Al-Mg-Si alloy with Sc and Zr additions" ARCHIVES OF METALLURGY AND MATERIALS, 51(4), 555-560 CODEN: AMMRCT; ISSN: 1733-3490, 2006, XP009137054**

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## Description

**[0001]** The present invention relates generally to aluminum alloys and more specifically to heat treatable aluminum alloys produced by melt processing and strengthened by  $L_{12}$  phase dispersions.

**[0002]** The combination of high strength, ductility, and fracture toughness, as well as low density, make aluminum alloys natural candidates for aerospace and space applications. However, their use is typically limited to temperatures below about 300°F (149°C) since most aluminum alloys start to lose strength in that temperature range as a result of coarsening of strengthening precipitates.

**[0003]** The development of aluminum alloys with improved elevated temperature mechanical properties is a continuing process. Some attempts have included aluminum-iron and aluminum-chromium based alloys such as Al-Fe-Ce, Al-Fe-V-Si, Al-Fe-Ce-W, and Al-Cr-Zr-Mn that contain incoherent dispersoids. These alloys, however, also lose strength at elevated temperatures due to particle coarsening. In addition, these alloys exhibit ductility and fracture toughness values lower than other commercially available aluminum alloys.

**[0004]** Other attempts have included the development of mechanically alloyed Al-Mg and Al-Ti alloys containing ceramic dispersoids. These alloys exhibit improved high temperature strength due to the particle dispersion, but the ductility and fracture toughness are not improved.

**[0005]** U.S. Patent No. 6,248,453 discloses aluminum alloys strengthened by dispersed  $Al_3X L_{12}$  intermetallic phases where X is selected from the group consisting of Sc, Er, Lu, Yb, Tm, and U. The  $Al_3X$  particles are coherent with the aluminum alloy matrix and are resistant to coarsening at elevated temperatures. The improved mechanical properties of the disclosed dispersion strengthened  $L_{12}$  aluminum alloys are stable up to 572°F (300°C). In order to create aluminum alloys containing fine dispersions of  $Al_3X L_{12}$  particles, the alloys need to be manufactured by expensive rapid solidification processes with cooling rates in excess of  $1.8 \times 10^3$ °F/sec ( $10^3$ °C/sec). U.S. Patent Application Publication No. 2006/0269437 discloses an aluminum alloy that contains scandium and other elements. While the alloy is effective at high temperatures, it is not capable of being heat treated using a conventional age hardening mechanism.

**[0006]** Heat treatable aluminum alloys strengthened by coherent  $L_{12}$  intermetallic phases produced by standard, inexpensive melt processing techniques would be useful.

**[0007]** JP 09104940 discloses an Al-Cu base alloy with various additions including scandium and zirconium.

**[0008]** Litynska Lidia et al: "Experimental and theoretical characterization of  $Al_3Sc$  precipitates in Al-Mg-Si-Cu-Sc-Zr alloys" and Litynska-Dobrzynska et al "Precipitation of phases in Al-Mg-Si-Cu alloy with Sc and Zr additions during heat treatment" both disclose Al-Mg-Si-Cu alloys with scandium and zirconium additions.

**[0009]** Cabibbo M et al: "A TEM study of the combined effect of severe plastic deformation and (Zr), (Sc + Zr) - containing dispersoids on an Al-Mg-Si alloy", US 2005/013725 and Litynska- Dobrzynska, L: "Effect of heat treatment on the sequence of phases formation in Al-Mg-Si alloy with Sc and Zr additions" all disclose Al-Mg-Si alloys with at least one of scandium or zirconium addition.

**[0010]** The present invention is heat treatable aluminum alloys that can be cast, wrought, or formed by rapid solidification, and thereafter heat treated. The alloys can achieve high temperature performance and can be used at temperatures up to about 650°F (343°C).

**[0011]** These alloys comprise silicon, magnesium, and an  $Al_3X L_{12}$  dispersoid where X is at least one first element selected from erbium, thulium, ytterbium, and lutetium, and at least one second element selected from gadolinium, yttrium, titanium, hafnium, and niobium. The balance is substantially aluminum.

**[0012]** The alloys may also have less than 1.0 weight percent total impurities.

**[0013]** The present invention provides a heat treatable aluminum alloy consisting of: 0.2 to 3.0 weight percent magnesium; at least one element selected from the group consisting of 0.1 to 2.0 weight percent silicon, and 0.1 to 2.0 weight percent manganese; at least one first element selected from the group consisting of 0.1 to 6.0 weight percent erbium, 0.1 to 10 weight percent thulium, 0.1 to 15.0 weight percent ytterbium, and 0.1 to 12 weight percent lutetium; at least one second element selected from the group consisting of 0.1 to 4.0 weight percent gadolinium, 0.1 to 4.0 weight percent yttrium, 0.05 to 2.0 weight percent titanium, 0.05 to 2.0 weight percent hafnium, and 0.05 to 1.0 weight percent niobium; optionally consisting of at least one of 0.001 to 0.1 weight percent sodium, 0.001 to 0.1 weight percent calcium, 0.001 to 0.1 weight percent strontium, 0.001 to 0.1 weight percent antimony, 0.001 to 0.1 weight percent barium, and 0.001 to 0.1 weight percent phosphorus, consisting of no more than 1.0 weight percent total other elements including impurities, and; optionally consisting of no more than 0.1 weight percent iron, 0.1 weight percent chromium, 0.1 weight percent vanadium, 0.1 weight percent cobalt, and 0.1 weight percent nickel; and the balance being aluminum with unavoidable impurities.

**[0014]** In another aspect the present invention provides a method of forming a heat treatable aluminum alloy, the method comprising: (a) forming a melt consisting of: 0.2 to 3.0 weight percent magnesium; at least one element selected from the group consisting of 0.1 to 2.0 weight percent silicon, and 0.1 to 2.0 weight percent manganese; at least one first element selected from the group consisting of 0.1 to 6.0 weight percent erbium, 0.1 to 10 weight percent thulium, 0.1 to 15.0 weight percent ytterbium, and 0.1 to 12 weight percent lutetium; at least one second element selected from the group consisting of 0.1 to 4.0 weight percent gadolinium, 0.1 to 4.0 weight percent yttrium, 0.05 to 2.0 weight percent titanium, 0.05

to 2.0 weight percent hafnium, and 0.05 to 1.0 weight percent niobium; optionally consisting of at least one of 0.001 to 0.1 weight percent sodium, 0.001 to 0.1 weight percent calcium, 0.001 to 0.1 weight percent strontium, 0.001 to 0.1 weight percent antimony, 0.001 to 0.1 weight percent barium, and 0.001 to 0.1 weight percent phosphorus, consisting of no more than 1.0 weight percent total other elements including impurities, and; optionally consisting of no more than 0.1 weight percent iron, 0.1 weight percent chromium, 0.1 weight percent vanadium, 0.1 weight percent cobalt, and 0.1 weight percent nickel; and the balance being aluminum with unavoidable impurities; (b) solidifying the melt to form a solid body; and (c) heat treating the solid body.

**[0015]** The alloys are formed by a process selected from casting, deformation processing and rapid solidification. The alloys are then heat treated at a temperature of from about 800°F (426°C) to about 1100°F (593°C) for between about 30 minutes and four hours, followed by quenching in water, and thereafter aged at a temperature from about 200°F (93°C) to about 600°F (315°C) for about two to forty eight hours.

**[0016]** Certain preferred embodiments of the invention will now be described by way of example only and with reference to the accompanying drawings.

FIG. 1 is an aluminum silicon phase diagram.  
 FIG. 2 is an aluminum magnesium phase diagram.  
 FIG. 3 is an aluminum manganese phase diagram.  
 FIG. 4 is an aluminum erbium phase diagram.  
 FIG. 5 is an aluminum thulium phase diagram.  
 FIG. 6 is an aluminum ytterbium phase diagram.  
 FIG. 7 is an aluminum lutetium phase diagram

**[0017]** The alloys of this invention are based on the aluminum-magnesium-silicon system. The aluminum silicon phase diagram is shown in FIG. 1. The binary system is a simple eutectic alloy system with a eutectic reaction at 12.5 weight percent silicon and 1077°F (577°C). There is little solubility of silicon in aluminum at temperatures up to 930°F (500°C) and none of aluminum in silicon. Hypoeutectic alloys with less than 12.6 weight percent silicon solidify with a microstructure consisting of primary aluminum grains in a finely divided aluminum/silicon eutectic matrix phase. Hypereutectic alloys with silicon contents greater than the eutectic composition solidify with a microstructure of primary silicon grains in a finely divided aluminum/silicon eutectic matrix phase. Alloys of this invention include alloys with the addition of about 0.1 to about 2.0 weight percent silicon, more preferably about 0.2 to about 1.6 weight percent silicon, and even more preferably about 0.3 to about 1.4 weight percent silicon.  
**[0018]** The alloys are formed by a process selected from casting, casting plus deformation processing and rapid solidification. Following formation the alloys are heat treated at a temperature from about 800°F (425°C) to about 1100°F (593°C) for between about 30 minutes and four hours, followed by quenching in a liquid, and

thereafter aged at a temperature from about 200°F (93°C) to about 600°F (315°C) for about two to about forty-eight hours. The alloys of this invention are based on the aluminum magnesium system. The aluminum magnesium phase diagram is shown in FIG. 2. The binary system is a eutectic alloy system with a eutectic reaction at 36 weight percent magnesium and 842°F (450°C). Magnesium has maximum solid solubility of 16 weight percent in aluminum at 842°F (450°C). The amount of magnesium in these alloys ranges from about 0.2 to about 3.0 weight percent, more preferably about 0.4 to about 2.0 weight percent, and even more preferably about 0.5 to about 1.6 weight percent. The ratio of magnesium to silicon is about 2.5:1, more preferably about 2:1, and even more preferably about 1.75:1.

**[0019]** The aluminum manganese phase diagram is shown in FIG. 3. The aluminum manganese binary system is a eutectic alloy system with a eutectic reaction at 2.0 weight percent manganese and 1216.4°F (658°C). Manganese has maximum solid solubility of about 2 weight percent in aluminum at 1216.4°F (658°C) which can be extended further by rapid solidification processing. Manganese provides a considerable amount of precipitation strengthening in aluminum by precipitation of fine Al<sub>6</sub>Mn second phases. The present invention is focused on hypoeutectic alloy composition ranges. The amount of manganese in these alloys ranges from about 0.1 to about 2.0 weight percent, more preferably about 0.2 to about 1.5 weight percent, and even more preferably about 0.3 to about 1.0 weight percent.

**[0020]** Aluminum-magnesium-silicon alloys can include manganese. Mg<sub>2</sub>Si and Si crystals precipitate in aluminum-magnesium-silicon alloys following a solution heat treatment, quench, and age process. Mg<sub>2</sub>Al<sub>3</sub> (β) phase precipitates as large intermetallic particles in high magnesium containing aluminum alloys which is not desired from a strengthening point of view. The presence of L1<sub>2</sub> phase prevents formation of β phase in this material which improves ductility and toughness of material. In the solid solutions of the alloys of this invention are dispersions of Al<sub>3</sub>X having an L1<sub>2</sub> structure where X is at least one first element selected from erbium, thulium, ytterbium, and lutetium. Also present is at least one second element selected from gadolinium, yttrium, titanium, hafnium, and niobium.

**[0021]** Exemplary aluminum alloys of this invention include, but are not limited to (in weight percent):

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-0.1-6)Er-(0.1-4)Gd;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-10)Tm-(0.1-4)Gd;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-15)Yb-(0.1-4)Gd;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-12)Lu-(0.1-4)Gd;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-6)Er-(0.1-4)Y;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-10)Tm-(0.1-4)Y;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-15)Yb-(0.1-4)Y;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-12)Lu-(0.1-4)Y;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-6)Er-(0.05-2)Ti;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-10)Tm-(0.05-2)Ti;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-15)Yb-(0.05-2)Ti;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-12)Lu-(0.05-2)Ti;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-6)Er-(0.05-2)Hf;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-10)Tm-(0.05-2)Hf;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-15)Yb-(0.05-2)Hf;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-12)Lu-(0.05-2)Hf;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-6)Er-(0.05-1)Nb;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-10)Tm-(0.05-1)Nb;  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-15)Yb-(0.05-1)Nb; and  
 about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-12)Lu-(0.05-1)Nb.

**[0022]** Examples of other alloys similar to the above are those alloys with the addition of about 0.1 to about 2.0 weight percent Mn, more preferably alloys with the addition of about 0.2 to about 1.5 weight percent Mn, and even more preferably alloys with the addition of about 0.3 to about 1.0 weight percent Mn.

**[0023]** In the inventive aluminum based alloys disclosed herein, erbium, thulium, ytterbium, and lutetium are potent strengtheners that have low diffusivity and low solubility in aluminum. All these elements form equilibrium  $Al_3X$  intermetallic dispersoids where X is at least one of erbium, ytterbium, lutetium, that have an  $L1_2$  structure that is an ordered face centered cubic structure with the X atoms located at the corners and aluminum atoms located on the cube faces of the unit cell.

**[0024]** Erbium forms  $Al_3Er$  dispersoids in the aluminum matrix that are fine and coherent with the aluminum matrix. The lattice parameters of aluminum and  $Al_3Er$  are close (0.405 nm and 0.417 nm respectively), indicating there is minimal driving force for causing growth of the  $Al_3Er$  dispersoids. This low interfacial energy makes the  $Al_3Er$  dispersoids thermally stable and resistant to coarsening up to temperatures as high as about 842°F (450°C). Addition of magnesium in solid solution in aluminum increases the lattice parameter of the aluminum matrix, and decreases the lattice parameter mismatch further increasing the resistance of the  $Al_3Er$  to coarsening. In the alloys of this invention, these  $Al_3Er$  dispersoids are made stronger and more resistant to coarsening at

elevated temperatures by adding suitable alloying elements such as gadolinium, yttrium, titanium, hafnium, niobium, or combinations thereof that enter  $Al_3Er$  in solution.

**[0025]** Thulium forms metastable  $Al_3Tm$  dispersoids in the aluminum matrix that are fine and coherent with the aluminum matrix. The lattice parameters of aluminum and  $Al_3Tm$  are close (0.405 nm and 0.420 nm respectively), indicating there is minimal driving force for causing growth of the  $Al_3Tm$  dispersoids. This low interfacial energy makes the  $Al_3Tm$  dispersoids thermally stable and resistant to coarsening up to temperatures as high as about 842°F (450°C). Addition of magnesium in solid solution in aluminum increases the lattice parameter of the aluminum matrix and decreases the lattice parameter mismatch further increasing the resistance to coarsening of the dispersoid. In the alloys of this invention these  $Al_3Tm$  dispersoids are made stronger and more resistant to coarsening at elevated temperatures by adding suitable alloying elements such as gadolinium, yttrium, titanium, hafnium, niobium, or combinations thereof that enter  $Al_3Tm$  in solution.

**[0026]** Ytterbium forms  $Al_3Yb$  dispersoids in the aluminum matrix that are fine and coherent with the aluminum matrix. The lattice parameters of Al and  $Al_3Yb$  are close (0.405 nm and 0.420 nm respectively), indicating there is minimal driving force for causing growth of the  $Al_3Yb$  dispersoids. This low interfacial energy makes the  $Al_3Yb$  dispersoids thermally stable and resistant to coarsening up to temperatures as high as about 842°F (450°C). Addition of magnesium in solid solution in aluminum increases the lattice parameter of the aluminum matrix and decreases the lattice parameter mismatch further increasing the resistance to coarsening of the  $Al_3Yb$ . In the alloys of this invention, these  $Al_3Yb$  dispersoids are made stronger and more resistant to coarsening at elevated temperatures by adding suitable alloying elements such as gadolinium, yttrium, titanium, hafnium, niobium, or combinations thereof that enter  $Al_3Yb$  in solution.

**[0027]** Lutetium forms  $Al_3Lu$  dispersoids in the aluminum matrix that are fine and coherent with the aluminum matrix. The lattice parameters of Al and  $Al_3Lu$  are close (0.405 nm and 0.419 nm respectively), indicating there is minimal driving force for causing growth of the  $Al_3Lu$  dispersoids. This low interfacial energy makes the  $Al_3Lu$  dispersoids thermally stable and resistant to coarsening up to temperatures as high as about 842°F (450°C). Addition of magnesium in solid solution in aluminum increases the lattice parameter of the aluminum matrix and decreases the lattice parameter mismatch further increasing the resistance to coarsening of  $Al_3Lu$ . In the alloys of this invention, these  $Al_3Lu$  dispersoids are made stronger and more resistant to coarsening at elevated temperatures by adding suitable alloying elements such as gadolinium, yttrium, titanium, hafnium, niobium, or mixtures thereof that enter  $Al_3Lu$  in solution.

**[0028]** Gadolinium forms metastable  $Al_3Gd$  dispersoids in the aluminum matrix that have an  $L1_2$  structure

in the metastable condition. The  $\text{Al}_3\text{Gd}$  dispersoids are stable up to temperatures as high as about 842°F (450°C) due to their low diffusivity in aluminum. The  $\text{Al}_3\text{Gd}$  dispersoids have a  $\text{D0}_{19}$  structure in the equilibrium condition. Despite its large atomic size, gadolinium has fairly high solubility in the  $\text{Al}_3\text{X}$  intermetallic dispersoids (where X is erbium, thulium, ytterbium or lutetium). Gadolinium can substitute for the X atoms in  $\text{Al}_3\text{X}$  intermetallic, thereby forming an ordered  $\text{L1}_2$  phase which results in improved thermal and structural stability.

**[0029]** Yttrium forms metastable  $\text{Al}_3\text{Y}$  dispersoids in the aluminum matrix that have an  $\text{L1}_2$  structure in the metastable condition and a  $\text{D0}_{19}$  structure in the equilibrium condition. The metastable  $\text{Al}_3\text{Y}$  dispersoids have a low diffusion coefficient which makes them thermally stable and highly resistant to coarsening. Yttrium has a high solubility in the  $\text{Al}_3\text{X}$  intermetallic dispersoids allowing large amounts of yttrium to substitute for X in the  $\text{Al}_3\text{X}$   $\text{L1}_2$  dispersoids which results in improved thermal and structural stability.

**[0030]** Titanium forms  $\text{Al}_3\text{Ti}$  dispersoids in the aluminum matrix that have an  $\text{L1}_2$  structure in the metastable condition and  $\text{D0}_{22}$  structure in the equilibrium condition. The metastable  $\text{Al}_3\text{Ti}$  dispersoids have a low diffusion coefficient which makes them thermally stable and highly resistant to coarsening. Titanium has a high solubility in the  $\text{Al}_3\text{X}$  dispersoids allowing large amounts of titanium to substitute for X in the  $\text{Al}_3\text{X}$  dispersoids, which results in improved thermal and structural stability.

**[0031]** Hafnium forms metastable  $\text{Al}_3\text{Hf}$  dispersoids in the aluminum matrix that have an  $\text{L1}_2$  structure in the metastable condition and a  $\text{D0}_{23}$  structure in the equilibrium condition. The  $\text{Al}_3\text{Hf}$  dispersoids have a low diffusion coefficient, which makes them thermally stable and highly resistant to coarsening. Hafnium has a high solubility in the  $\text{Al}_3\text{X}$  dispersoids allowing large amounts of hafnium to substitute for erbium, thulium, ytterbium, and lutetium in the above mentioned  $\text{Al}_3\text{X}$  dispersoids, which results in stronger and more thermally stable dispersoids.

**[0032]** Niobium forms metastable  $\text{Al}_3\text{Nb}$  dispersoids in the aluminum matrix that have an  $\text{L1}_2$  structure in the metastable condition and a  $\text{D0}_{22}$  structure in the equilibrium condition. Niobium has a lower solubility in the  $\text{Al}_3\text{X}$  dispersoids than hafnium or yttrium, allowing relatively lower amounts of niobium than hafnium or yttrium to substitute for X in the  $\text{Al}_3\text{X}$  dispersoids. Nonetheless, niobium can be very effective in slowing down the coarsening kinetics of the  $\text{Al}_3\text{X}$  dispersoids because the  $\text{Al}_3\text{Nb}$  dispersoids are thermally stable. The substitution of niobium for X in the above mentioned  $\text{Al}_3\text{X}$  dispersoids results in stronger and more thermally stable dispersoids.

**[0033]**  $\text{Al}_3\text{X}$   $\text{L1}_2$  precipitates improve elevated temperature mechanical properties in aluminum alloys for two reasons. First, the precipitates are ordered intermetallic compounds. As a result, when the particles are sheared by glide dislocations during deformation, the dislocations separate into two partial dislocations separated by an anti-phase boundary on the glide plane. The energy to

create the anti-phase boundary is the origin of the strengthening. Second, the cubic  $\text{L1}_2$  crystal structure and lattice parameter of the precipitates are closely matched to the aluminum solid solution matrix. This results in a lattice coherency at the precipitate/matrix boundary that resists coarsening. The lack of an inter-phase boundary results in a low driving force for particle growth and resulting elevated temperature stability. Alloying elements in solid solution in the dispersed strengthening particles and in the aluminum matrix that tend to decrease the lattice mismatch between the matrix and particles will tend to increase the strengthening and elevated temperature stability of the alloy.

**[0034]** The amount of erbium present in the alloys of this invention, if any, may vary from about 0.1 to about 6.0 weight percent, more preferably from about 0.1 to about 4 weight percent, and even more preferably from about 0.2 to 2 weight percent. The Al-Er phase diagram shown in FIG. 4 indicates a eutectic reaction at about 6 weight percent erbium at about 1211°F (655°C). Aluminum alloys with less than about 6 weight percent erbium can be quenched from the melt to retain erbium in solid solutions that may precipitate as dispersed  $\text{L1}_2$  intermetallic  $\text{Al}_3\text{Er}$  following an aging treatment. Alloys with erbium in excess of the eutectic composition can only retain erbium in solid solution by rapid solidification processing (RSP) where cooling rates are in excess of about 10<sup>3</sup>°C/second. Alloys with erbium in excess of the eutectic composition (hypereutectic alloys) cooled normally will have a microstructure consisting of relatively large  $\text{Al}_3\text{Er}$  dispersoid in a finely divided aluminum- $\text{Al}_3\text{Er}$  eutectic phase matrix.

**[0035]** The amount of thulium present in the alloys of this invention, if any, may vary from about 0.1 to about 10 weight percent, more preferably from about 0.2 to about 6 weight percent, and even more preferably from about 0.2 to about 4 weight percent. The Al-Tm phase diagram shown in FIG. 5 indicates a eutectic reaction at about 10 weight percent thulium at about 1193°F (645°C). Thulium forms metastable  $\text{Al}_3\text{Tm}$  dispersoids in the aluminum matrix that have an  $\text{L1}_2$  structure in the equilibrium condition. The  $\text{Al}_3\text{Tm}$  dispersoids have a low diffusion coefficient which makes them thermally stable and highly resistant to coarsening. Aluminum alloys with less than 10 weight percent thulium can be quenched from the melt to retain thulium in solid solution that may precipitate as dispersed metastable  $\text{L1}_2$  intermetallic  $\text{Al}_3\text{Tm}$  following an aging treatment. Alloys with thulium in excess of the eutectic composition can only retain Tm in solid solution by rapid solidification processing (RSP) where cooling rates are in excess of about 10<sup>3</sup>°C/second.

**[0036]** The amount of ytterbium present in the alloys of this invention, if any, may vary from about 0.1 to about 15 weight percent more preferably from about 0.2 to about 8 weight percent, and even more preferably from about 0.2 to about 4 weight percent. The Al-Yb phase diagram shown in FIG. 6 indicates a eutectic reaction at about 21 weight percent ytterbium at about 1157°F

(625°C). Aluminum alloys with less than about 21 weight percent ytterbium can be quenched from the melt to retain ytterbium in solid solution that may precipitate as dispersed  $L1_2$  intermetallic  $Al_3Yb$  following an aging treatment. Alloys with ytterbium in excess of the eutectic composition can only retain ytterbium in solid solution by rapid solidification processing (RSP) where cooling rates are in excess of about  $10^3$ °C/second.

**[0037]** The amount of lutetium present in the alloys of this invention, if any, may vary from about 0.1 to about 12 weight percent, more preferably from 0.2 to about 8 weight percent, and even more preferably from about 0.2 to about 4 weight percent. The Al-Lu phase diagram shown in FIG. 7 indicates a eutectic reaction at about 11.7 weight percent Lu at about 1202°F (650°C). Aluminum alloys with less than about 11.7 weight percent lutetium can be quenched from the melt to retain Lu in solid solution that may precipitate as dispersed  $L1_2$  intermetallic  $Al_3Lu$  following an aging treatment. Alloys with Lu in excess of the eutectic composition can only retain Lu in solid solution by rapid solidification processing (RSP) where cooling rates are in excess of about  $10^3$ °C/second.

**[0038]** The amount of gadolinium present in the alloys of this invention, if any, may vary from about 0.1 to about 4 weight percent, more preferably from 0.2 to about 2 weight percent, and even more preferably from about 0.5 to about 2 weight percent.

**[0039]** The amount of yttrium present in the alloys of this invention, if any, may vary from about 0.1 to about 4 weight percent, more preferably from 0.2 to about 2 weight percent, and even more preferably from about 0.5 to about 2 weight percent.

**[0040]** The amount of titanium present in the alloys of this invention, if any, may vary from about 0.05 to 2 about weight percent, more preferably from 0.1 to about 1 weight percent, and even more preferably from about 0.1 to about 0.5 weight percent.

**[0041]** The amount of hafnium present in the alloys of this invention, if any, may vary from about 0.05 to about 2 weight percent, more preferably from 0.1 to about 1 weight percent, and even more preferably from about 0.1 to about 0.5 weight percent.

**[0042]** The amount of niobium present in the alloys of this invention, if any, may vary from about 0.05 to about 1 weight percent, more preferably from 0.1 to about 0.75 weight percent, and even more preferably from about 0.1 to about 0.5 weight percent.

**[0043]** In order to have the best properties for the alloys of this invention, it is desirable to limit the amount of other elements. Specific elements that should be reduced or eliminated include no more than about 0.1 weight percent iron, 0.1 weight percent chromium, 0.1 weight percent vanadium, 0.1 weight percent cobalt, and 0.1 weight percent nickel. The total quantity of additional elements should not exceed about 1% by weight, including the above listed elements.

**[0044]** Other additions in the inventive alloys include at least one of about 0.001 weight percent to about 0.10

weight percent sodium, about 0.001 weight percent to about 0.10 weight percent calcium, about 0.001 to about 0.10 weight percent strontium, about 0.001 to about 0.10 weight percent antimony, 0.001 to 0.10 weight percent barium and about 0.001 to about 0.10 weight percent phosphorus. These are added to refine the microstructure of the eutectic phase and the primary silicon particle morphology and size.

**[0045]** These aluminum alloys may be made by any and all consolidation and fabrication processes known to those in the art such as casting (without further deformation), deformation processing (wrought processing), rapid solidification processing, forging, extrusion, rolling, die forging, powder metallurgy and others. The rapid solidification process should have a cooling rate greater than about  $10^3$ °C/second including but not limited to powder processing, atomization, melt spinning, splat quenching, spray deposition, cold spray, plasma spray, laser melting and deposition, ball milling and cryomilling.

**[0046]** Preferred exemplary aluminum alloys of this invention include, but are not limited to (in weight percent):

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-4)Er-(0.2-2)Gd;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-6)Tm-(0.2-2)Gd;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Yb-(0.2-2)Gd;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Lu-(0.2-2)Gd;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.1-4)Er-(0.2-2)Y;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-6)Tm-(0.2-2)Y;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Yb-(0.2-2)Y;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Lu-(0.2-2)Y;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg(0.1-4)Er-(0.1-1)Ti;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-6)Tm-(0.1-1)Ti;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Yb-(0.1-1)Ti;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Lu-(0.1-1)Ti;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg(0.1-4)Er-(0.1-1)Hf;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-6)Tm-(0.1-1)Hf;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Yb-(0.1-1)Hf;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Lu-(0.1-1)Hf;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-2)Er-(0.1-0.75)Nb;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-6)Tm-(0.1-0.75)Nb;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Yb-(0.1-0.75)Nb; and

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-8)Lu-(0.1-

0.75)Nb.

**[0047]** Examples of other alloys similar to the above are alloys with the addition of about 0.1 to about 2.0 weight percent Mn, more preferably alloys with the addition of about 0.2 to about 1.5 weight percent Mn, and even more preferably alloys with the addition of about 0.3 to about 1.0 weight percent Mn.

**[0048]** Even more preferred exemplary aluminum alloys of this invention include, but are not limited to (in weight percent):

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-2)Er-(0.5-2)Gd;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Tm-(0.5-2)Gd;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Yb-(0.5-2)Gd;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Lu-(0.5-2)Gd;

about Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-2)Er-(0.5-2)Y;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Tm-(0.5-2)Y;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Yb-(0.5-2)Y;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Lu-(0.5-2)Y;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-2)Er-(0.1-0.5)Zr;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Tm-(0.1-0.5)Zr;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Yb-(0.1-0.5)Zr;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Lu-(0.1-0.5)Zr;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-2)Er-(0.1-0.5)Hf;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Tm-(0.1-0.5)Hf;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Yb-(0.1-0.5)Hf;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Lu-(0.1-0.5)Hf;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-2)Er-(0.1-0.5)Nb;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Tm-(0.1-0.5)Nb;

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Yb-(0.1-0.5)Nb;

and

about

Al-(0.1-2.0)Si-(0.2-3.0)Mg-(0.2-4)Lu-(0.1-0.5)Nb.

**[0049]** Examples of other alloys similar to these are alloys with the addition of about 0.1 to about 2.0 weight percent Mn, more preferably alloys with the addition of about 0.2 to about 1.5 weight percent Mn, and even more preferably alloys with the addition of about 0.3 to about

1.0 weight percent Mn.

**[0050]** Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the scope of the invention as defined by the attached claims.

**[0051]** One aspect of at least the preferred embodiment of the present invention is a heat treatable aluminum alloy comprising about 0.2 to about 3.0 weight percent magnesium, at least one element selected from the group consisting of about 0.1 to about 2.0 weight percent silicon, and about 0.1 to about 2.0 weight percent manganese; an aluminum solid solution matrix containing a plurality of dispersed  $Al_3X$  second phases having  $L1_2$  structures where X comprises at least one of erbium, thulium, ytterbium, lutetium, and at least one of gadolinium, yttrium, titanium, hafnium, niobium.

**[0052]** Preferably wherein the alloy comprises an aluminum solid solution matrix, precipitates including but not limited to  $Mg_2Si$ ,  $Al_6Mn$ , and a plurality of dispersed  $Al_3X$  second phases having  $L1_2$  structures where X comprises at least one of erbium, thulium, ytterbium, lutetium, and at least one of gadolinium, yttrium, titanium, hafnium, niobium.

**[0053]** Preferably wherein the alloy comprises at least one of about 0.1 to about 6.0 weight percent erbium, about 0.1 to about 10 weight percent thulium, about 0.1 to about 15.0 weight percent ytterbium, about 0.1 to about 12 weight percent lutetium, and about 0.1 to about 4.0 weight percent gadolinium, about 0.1 to about 4.0 weight percent yttrium, about 0.05 to about 1.0 weight percent zirconium, about 0.05 to about 2.0 weight percent titanium, about 0.05 to about 2.0 weight percent hafnium, and about 0.05 to about 1.0 weight percent niobium.

## Claims

1. A heat treatable aluminum alloy consisting of:

0.2 to 3.0 weight percent magnesium;

at least one element selected from the group consisting of 0.1 to 2.0 weight percent silicon, and 0.1 to 2.0 weight percent manganese;

at least one first element selected from the group consisting of 0.1 to 6.0 weight percent erbium, 0.1 to 10 weight percent thulium, 0.1 to 15.0 weight percent ytterbium, and 0.1 to 12 weight percent lutetium;

at least one second element selected from the group consisting of 0.1 to 4.0 weight percent gadolinium, 0.1 to 4.0 weight percent yttrium, 0.05 to 2.0 weight percent titanium, 0.05 to 2.0 weight percent hafnium, and 0.05 to 1.0 weight percent niobium;

optionally consisting of at least one of 0.001 to 0.1 weight percent sodium, 0.001 to 0.1 weight percent calcium, 0.001 to 0.1 weight percent

strontium, 0.001 to 0.1 weight percent antimony, 0.001 to 0.1 weight percent barium, and 0.001 to 0.1 weight percent phosphorus, consisting of no more than 1.0 weight percent total other elements including impurities, and; optionally consisting of no more than 0.1 weight percent iron, 0.1 weight percent chromium, 0.1 weight percent vanadium, 0.1 weight percent cobalt, and 0.1 weight percent nickel; and

the balance being aluminum with unavoidable impurities.

2. The alloy of claim 1, wherein the alloy comprises an aluminum solid solution matrix containing a plurality of dispersed Al<sub>3</sub>X second phases having L1<sub>2</sub> structures, wherein X includes at least one first element and at least one second element.

3. The alloy of claim 1, wherein the alloy comprises an aluminum solid solution matrix and precipitates including but not limited to Mg<sub>2</sub>Si, and Al<sub>6</sub>Mn; a plurality of dispersed Al<sub>3</sub>X second phases having L1<sub>2</sub> structures, wherein X includes at least one first element selected from the group consisting of 0.1 to 6.0 weight percent erbium, 0.1 to 10 weight percent thulium, 0.1 to 15.0 weight percent ytterbium, and 0.1 to 12 weight percent lutetium; and at least one second element selected from the group consisting of 0.1 to 4.0 weight percent gadolinium, 0.1 to 4.0 weight percent yttrium, 0.05 to 2.0 weight percent titanium, 0.05 to 2.0 weight percent hafnium, and 0.05 to 1.0 weight percent niobium; and the balance being aluminum with unavoidable impurities.

4. The alloy of claim 1, 2 or 3, wherein the at least one element selected from the group consisting of 0.1 to 2.0 weight percent silicon, 0.2 to 6.5 weight percent copper, 0.1 to 2.0 weight percent manganese is 0.1 to 2.0 weight percent silicon.

5. The alloy of any preceding claim, wherein the amount of silicon ranges from 0.2 to 1.6 weight percent.

6. The alloy of claim 1, 2 or 3, wherein the at least one element selected from the group consisting of 0.1 to 2.0 weight percent silicon, and 0.1 to 2.0 weight percent manganese is 0.1 to 2.0 weight percent manganese.

7. A method of forming a heat treatable aluminum alloy, the method comprising:

(a) forming a melt consisting of:

0.2 to 3.0 weight percent magnesium;

at least one element selected from the group consisting of 0.1 to 2.0 weight percent silicon, and 0.1 to 2.0 weight percent manganese;

at least one first element selected from the group consisting of 0.1 to 6.0 weight percent erbium, 0.1 to 10 weight percent thulium, 0.1 to 15.0 weight percent ytterbium, and 0.1 to 12 weight percent lutetium;

at least one second element selected from the group consisting of 0.1 to 4.0 weight percent gadolinium, 0.1 to 4.0 weight percent yttrium, 0.05 to 2.0 weight percent titanium, 0.05 to 2.0 weight percent hafnium, and 0.05 to 1.0 weight percent niobium; optionally consisting of at least one of 0.001 to 0.1 weight percent sodium, 0.001 to 0.1 weight percent calcium, 0.001 to 0.1 weight percent strontium, 0.001 to 0.1 weight percent antimony, 0.001 to 0.1 weight percent barium, and 0.001 to 0.1 weight percent phosphorus, consisting of no more than 1.0 weight percent total other elements including impurities, and;

optionally consisting of no more than 0.1 weight percent iron, 0.1 weight percent chromium, 0.1 weight percent vanadium, 0.1 weight percent cobalt, and 0.1 weight percent nickel; and

the balance being aluminum with unavoidable impurities.

(b) solidifying the melt to form a solid body; and  
(c) heat treating the solid body.

8. The method of claim 7 further comprising: refining the structure of the solid body by deformation processing including but not limited to these processes: extrusion, forging and rolling.

9. The method of claim 7 or 8, wherein solidifying comprises a rapid solidification process in which the cooling rate is greater than 10<sup>3</sup>°C/second including at least one of: powder processing, atomization, melt spinning, splat quenching, spray deposition, cold spray, plasma spray, laser melting and deposition, ball milling, and cryomilling.

10. The method of claim 7, 8 or 9, wherein the heat treating comprises:

solution heat treatment at 800°F (426°C) to 1100°F (593°C) for thirty minutes to four hours; and  
quenching; and  
aging at a temperature of 200°F (93°C) to 600°F (315°C) for two to forty eight hours.

11. The method of claim 7 comprising forming the alloy by a process selected from casting, and subsequent deformation processing, and rapid solidification processing.

### Patentansprüche

1. Hitzebehandelbare Aluminiumlegierung, die aus Folgendem besteht:

0,2 bis 3,0 Gewichtsprozent Magnesium; mindestens einem Element, ausgewählt aus der Gruppe bestehend aus 0,1 bis 2,0 Gewichtsprozent Silicium und 0,1 bis 2,0 Gewichtsprozent Mangan; mindestens einem ersten Element, ausgewählt aus der Gruppe bestehend aus 0,1 bis 6,0 Gewichtsprozent Erbium, 0,1 bis 10 Gewichtsprozent Thulium, 0,1 bis 15,0 Gewichtsprozent Ytterbium und 0,1 bis 12 Gewichtsprozent Lutetium; mindestens einem zweiten Element, ausgewählt aus der Gruppe bestehend aus 0,1 bis 4,0 Gewichtsprozent Gadolinium, 0,1 bis 4,0 Gewichtsprozent Yttrium, 0,05 bis 2,0 Gewichtsprozent Titan, 0,05 bis 2,0 Gewichtsprozent Hafnium und 0,05 bis 1,0 Gewichtsprozent Niob; wahlweise bestehend aus mindestens einem von 0,001 bis 0,1 Gewichtsprozent Natrium, 0,001 bis 0,1 Gewichtsprozent Calcium, 0,001 bis 0,1 Gewichtsprozent Strontium, 0,001 bis 0,1 Gewichtsprozent Antimon, 0,001 bis 0,1 Gewichtsprozent Barium und 0,001 bis 0,1 Gewichtsprozent Phosphor, bestehend aus nicht mehr als insgesamt 1,0 Gewichtsprozent von anderen Elementen, einschließlich Verunreinigungen, und; wahlweise bestehend aus nicht mehr als 0,1 Gewichtsprozent Eisen, 0,1 Gewichtsprozent Chrom, 0,1 Gewichtsprozent Vanadium, 0,1 Gewichtsprozent Cobalt und 0,1 Gewichtsprozent Nickel; und wobei der Rest Aluminium mit unvermeidbaren Verunreinigungen ist.

2. Legierung nach Anspruch 1, wobei die Legierung eine Aluminiumfeststofflösungsmatrix umfasst, die eine Vielzahl von dispergierten  $Al_3X$ -Zweitphasen enthält, die  $L1_2$ -Strukturen aufweisen, wobei X mindestens ein erstes Element und mindestens ein zweites Element beinhaltet.
3. Legierung nach Anspruch 1, wobei die Legierung eine Aluminiumfeststofflösungsmatrix umfasst und einschließlich unter anderem  $Mg_2Si$  und  $Al_6Mn$  ausfällt; wobei eine Vielzahl von dispergierten  $Al_3X$ -Zweit-

phasen  $L1_2$ -Strukturen aufweisen, wobei X mindestens ein erstes Element beinhaltet, ausgewählt aus der Gruppe bestehend aus 0,1 bis 6,0 Gewichtsprozent Erbium, 0,1 bis 10 Gewichtsprozent Thulium, 0,1 bis 15,0 Gewichtsprozent Ytterbium und 0,1 bis 12 Gewichtsprozent Lutetium; und wobei mindestens ein zweites Element ausgewählt ist aus der Gruppe bestehend aus 0,1 bis 4,0 Gewichtsprozent Gadolinium, 0,1 bis 4,0 Gewichtsprozent Yttrium, 0,05 bis 2,0 Gewichtsprozent Titan, 0,05 bis 2,0 Gewichtsprozent Hafnium und 0,05 bis 1,0 Gewichtsprozent Niob; und wobei der Rest Aluminium mit unvermeidbaren Verunreinigungen ist.

4. Legierung nach Anspruch 1, 2 oder 3, wobei das mindestens eine Element, das ausgewählt ist aus der Gruppe bestehend aus 0,1 bis 2,0 Gewichtsprozent Silicium, 0,2 bis 6,5 Gewichtsprozent Kupfer, 0,1 bis 2,0 Gewichtsprozent Mangan, zu 0,1 bis 2,0 Gewichtsprozent Silicium ist.
5. Legierung nach einem der vorhergehenden Ansprüche, wobei die Menge von Silicium im Bereich von 0,1 bis 1,6 Gewichtsprozent liegt.
6. Legierung nach Anspruch 1, 2 oder 3, wobei das mindestens eine Element, das ausgewählt ist aus der Gruppe bestehend aus 0,1 bis 2,0 Gewichtsprozent Silicium und 0,1 bis 2,0 Gewichtsprozent Mangan, zu 0,1 bis 2,0 Gewichtsprozent Mangan ist.
7. Verfahren zum Bilden einer hitzebehandelbaren Aluminiumlegierung, wobei das Verfahren Folgendes umfasst:

(a) Bilden einer Schmelze, die aus Folgendem besteht:

0,2 bis 3,0 Gewichtsprozent Magnesium; mindestens einem Element, ausgewählt aus der Gruppe bestehend aus 0,1 bis 2,0 Gewichtsprozent Silicium und 0,1 bis 2,0 Gewichtsprozent Mangan; mindestens einem ersten Element, ausgewählt aus der Gruppe bestehend aus 0,1 bis 6,0 Gewichtsprozent Erbium, 0,1 bis 10 Gewichtsprozent Thulium, 0,1 bis 15,0 Gewichtsprozent Ytterbium und 0,1 bis 12 Gewichtsprozent Lutetium; mindestens einem zweiten Element, ausgewählt aus der Gruppe bestehend aus 0,1 bis 4,0 Gewichtsprozent Gadolinium, 0,1 bis 4,0 Gewichtsprozent Yttrium, 0,05 bis 2,0 Gewichtsprozent Titan, 0,05 bis 2,0 Gewichtsprozent Hafnium und 0,05 bis 1,0 Gewichtsprozent Niob; wahlweise bestehend aus mindestens ei-

- nem von 0,001 bis 0,1 Gewichtsprozent Natrium, 0,001 bis 0,1 Gewichtsprozent Calcium, 0,001 bis 0,1 Gewichtsprozent Strontium, 0,001 bis 0,1 Gewichtsprozent Antimon, 0,001 bis 0,1 Gewichtsprozent Barium und 0,001 bis 0,1 Gewichtsprozent Phosphor, bestehend aus nicht mehr als insgesamt 1,0 Gewichtsprozent von anderen Elementen, einschließlich Verunreinigungen, und;
- wahlweise bestehend aus nicht mehr als 0,1 Gewichtsprozent Eisen, 0,1 Gewichtsprozent Chrom, 0,1 Gewichtsprozent Vanadium, 0,1 Gewichtsprozent Cobalt und 0,1 Gewichtsprozent Nickel; und wobei der Rest Aluminium mit unvermeidbaren Verunreinigungen ist.
- (b) Verfestigen der Schmelze, um einen Festkörper zu bilden; und
- (c) Hitzebehandeln des Festkörpers.
8. Verfahren nach Anspruch 7, das ferner Folgendes umfasst: Verfeinern der Struktur des Festkörpers durch Verformungsbearbeitung, einschließlich unter anderem dieser Prozesse: Extrusion, Schmieden und Rollen.
9. Verfahren nach Anspruch 7 oder 8, wobei das Verfestigen einen schnellen Verfestigungsprozess umfasst, in welchem die Abkühlungsrate größer als  $10^3$  °C/Sekunde ist, einschließlich mindestens einem von: Pulververarbeitung, Atomisierung, Schmelzspinnen, Abschrecken aus der Schmelze, Sprühabscheidung, Kältsprühen, Plasmasprühen, Laserschmelzen und -abscheidung, Kugelmahlen und kryogenes Mahlen.
10. Verfahren nach Anspruch 7, 8 oder 9, wobei das Hitzebehandeln Folgendes umfasst:
- Hitzebehandlung der Lösung bei 800 °F (426 °C) bis 1100 °F (593 °C) für dreißig Minuten bis vier Stunden; und Abschrecken; und Altern bei einer Temperatur von 200 °F (93 °C) bis 600 °F (315 °C) für zwei bis achtundvierzig Stunden.
11. Verfahren nach Anspruch 7, das Bilden der Legierung durch einen Prozess umfasst, der ausgewählt ist aus Gießen und nachfolgendem Verformungsarbeiten und schnellem Verfestigungsarbeiten.
- Revendications**
1. Alliage d'aluminium à traitement thermique composé de :
- 0,2 à 3,0 pourcent en poids de magnésium ; au moins un élément choisi dans un groupe composé de 0,1 à 2,0 pourcent en poids de silicium, et 0,1 à 2,0 pourcent en poids de manganèse ; au moins un premier élément choisi dans un groupe composé de 0,1 à 6,0 pourcent en poids d'erbium, 0,1 à 10 pourcent en poids de thulium, 0,1 à 15,0 pourcent en poids d'ytterbium, et 0,1 à 12 pourcent en poids de lutétium ; au moins un second élément choisi dans un groupe composé de 0,1 à 4,0 pourcent en poids de gadolinium, 0,1 à 4,0 pourcent en poids d'yttrium, 0,05 à 2,0 pourcent en poids de titane, 0,05 à 2,0 pourcent en poids d'hafnium, et 0,05 à 1,0 pourcent en poids de niobium ; éventuellement composé d'au moins un de 0,001 à 0,1 pourcent en poids de sodium, 0,001 à 0,1 pourcent en poids de calcium, 0,001 à 0,1 pourcent en poids de strontium, 0,001 à 0,1 pourcent en poids d'antimoine, 0,001 à 0,1 pourcent en poids de baryum, et 0,001 à 0,1 pourcent en poids de phosphore, composé de pas plus de 1,0 pourcent en poids total d'autres éléments incluant des impuretés, et ; éventuellement composé de pas plus de 0,1 pourcent en poids de fer, 0,1 pourcent en poids de chrome, 0,1 pourcent en poids de vanadium, 0,1 pourcent en poids de cobalt, et 0,1 pourcent en poids de nickel ; et le reste étant de l'aluminium avec des impuretés inévitables.
2. Alliage selon la revendication 1, dans lequel l'alliage comprend une matrice de solution solide d'aluminium contenant une pluralité de secondes phases d' $Al_3X$  dispersées ayant des structures  $L1_2$ , dans lequel X inclut au moins un premier élément et au moins un second élément.
3. Alliage selon la revendication 1, dans lequel l'alliage comprend une matrice de solution solide d'aluminium et des précipités incluant mais sans limitation du  $Mg_2Si$ , et de l' $Al_6Mn$  ; une pluralité de secondes phases d' $Al_3X$  dispersées ayant des structures  $L1_2$ , dans lequel X inclut au moins un premier élément choisi dans un groupe composé de 0,1 à 6,0 pourcent en poids d'erbium, 0,1 à 10 pourcent en poids de thulium, 0,1 à 15,0 pourcent en poids d'ytterbium, et 0,1 à 12 pourcent en poids de lutétium ; et au moins un second élément choisi dans un groupe composé de 0,1 à 4,0 pourcent en poids de gadolinium, 0,1 à 4,0 pourcent en poids d'yttrium, 0,05 à 2,0 pourcent en poids de titane, 0,05 à 2,0 pourcent en poids d'hafnium, et 0,05 à 1,0 pourcent en poids de niobium ; et le reste étant de l'aluminium avec des impuretés iné-

vitables.

4. Alliage selon la revendication 1, 2 ou 3, dans lequel l'au moins un élément choisi dans un groupe composé de 0,1 à 2,0 pourcent en poids de silicium, 0,2 à 6,5 pourcent en poids de cuivre, 0,1 à 2,0 pourcent en poids de manganèse est 0,1 à 2,0 pourcent en poids de silicium. 5
5. Alliage selon une quelconque revendication précédente, dans lequel la quantité de silicium s'inscrit dans la plage de 0,2 à 1,6 pourcent en poids. 10
6. Alliage selon la revendication 1, 2 ou 3, dans lequel l'au moins un élément choisi dans un groupe composé de 0,1 à 2,0 pourcent en poids de silicium, et 0,1 à 2,0 pourcent en poids de manganèse est 0,1 à 2,0 pourcent en poids de manganèse. 15
7. Procédé de formation d'un alliage d'aluminium à traitement thermique, le procédé comprenant : 20
- (a) la formation d'une fonte composée de :
- 0,2 à 3,0 pourcent en poids de magnésium ; 25
- au moins un élément choisi dans un groupe composé de 0,1 à 2,0 pourcent en poids de silicium, et 0,1 à 2,0 pourcent en poids de manganèse ;
- au moins un premier élément choisi dans un groupe composé de 0,1 à 6,0 pourcent en poids d'erbium, 0,1 à 10 pourcent en poids de thulium, 0,1 à 15,0 pourcent en poids d'ytterbium, et 0,1 à 12 pourcent en poids de lutétium ; 30
- au moins un second élément choisi dans un groupe composé de 0,1 à 4,0 pourcent en poids de gadolinium, 0,1 à 4,0 pourcent en poids d'yttrium, 0,05 à 2,0 pourcent en poids de titane, 0,05 à 2,0 pourcent en poids d'hafnium, et 0,05 à 1,0 pourcent en poids de niobium ; 40
- éventuellement composé d'au moins 0,001 à 0,1 pourcent en poids de sodium, 0,001 à 0,1 pourcent en poids de calcium, 0,001 à 0,1 pourcent en poids de strontium, 0,001 à 0,1 pourcent en poids d'antimoine, 0,001 à 0,1 pourcent en poids de baryum, et 0,001 à 0,1 pourcent en poids de phosphore, composé de pas plus de 1,0 pourcent en poids total d'autres éléments incluant des impuretés, et ; 50
- éventuellement composé de pas plus de 0,1 pourcent en poids de fer, 0,1 pourcent en poids de chrome, 0,1 pourcent en poids de vanadium, 0,1 pourcent en poids de cobalt, et 0,1 pourcent en poids de nickel ; et 55
- le reste étant de l'aluminium avec des im-

puretés inévitables ;

- (b) la solidification de la fonte pour former un corps solide ; et
- (c) le traitement thermique du corps solide.
8. Procédé selon la revendication 7 comprenant en outre : l'affinement de la structure du corps solide par un processus de déformation incluant mais sans limitation ces procédés : une extrusion, un forgeage et un laminage.
9. Procédé selon la revendication 7 ou 8, dans lequel la solidification comprend un procédé de solidification rapide dans lequel la vitesse de refroidissement est supérieure à  $10^3$  °C/seconde incluant au moins un de : un processus de poudre, une atomisation, un filage par fusion, une hypertrempe, un dépôt par pulvérisation, une projection à froid, une projection au plasma, une fusion et un dépôt par laser, un broyage à boulets, et un cryobroyage.
10. Procédé selon la revendication 7, 8 ou 9, dans lequel le traitement thermique comprend : un traitement thermique de mise en solution à 800 °F (426 °C) à 1 100 °F (593 °C) pendant trente minutes à quatre heures ; et une trempe ; et un vieillissement à une température de 200 °F (93 °C) à 600 °F (315 °C) pendant deux à quarante-huit heures.
11. Procédé selon la revendication 7 comprenant la formation de l'alliage par un procédé choisi parmi un moulage, et un processus de déformation ultérieur, et un processus de solidification rapide.

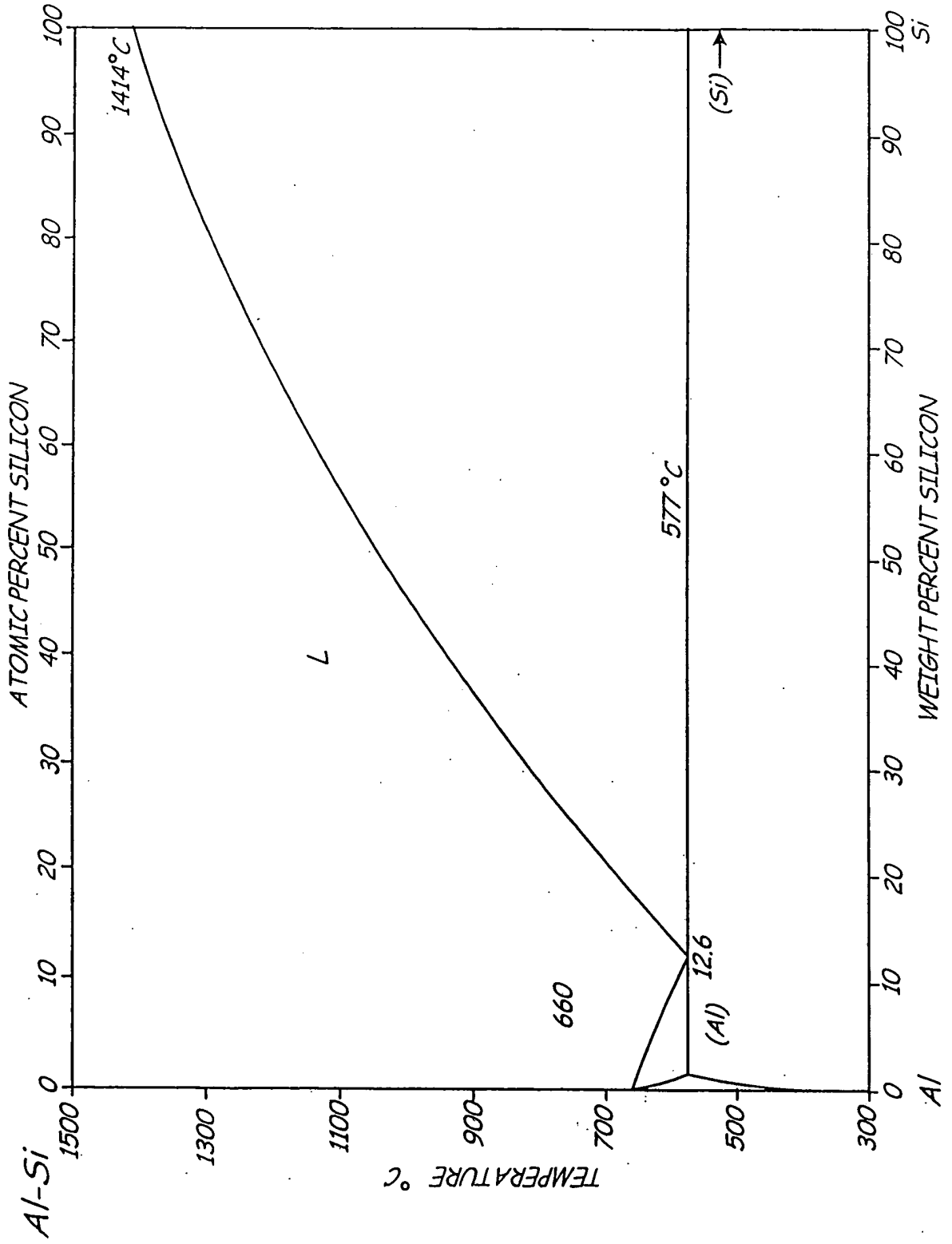


FIG. 1

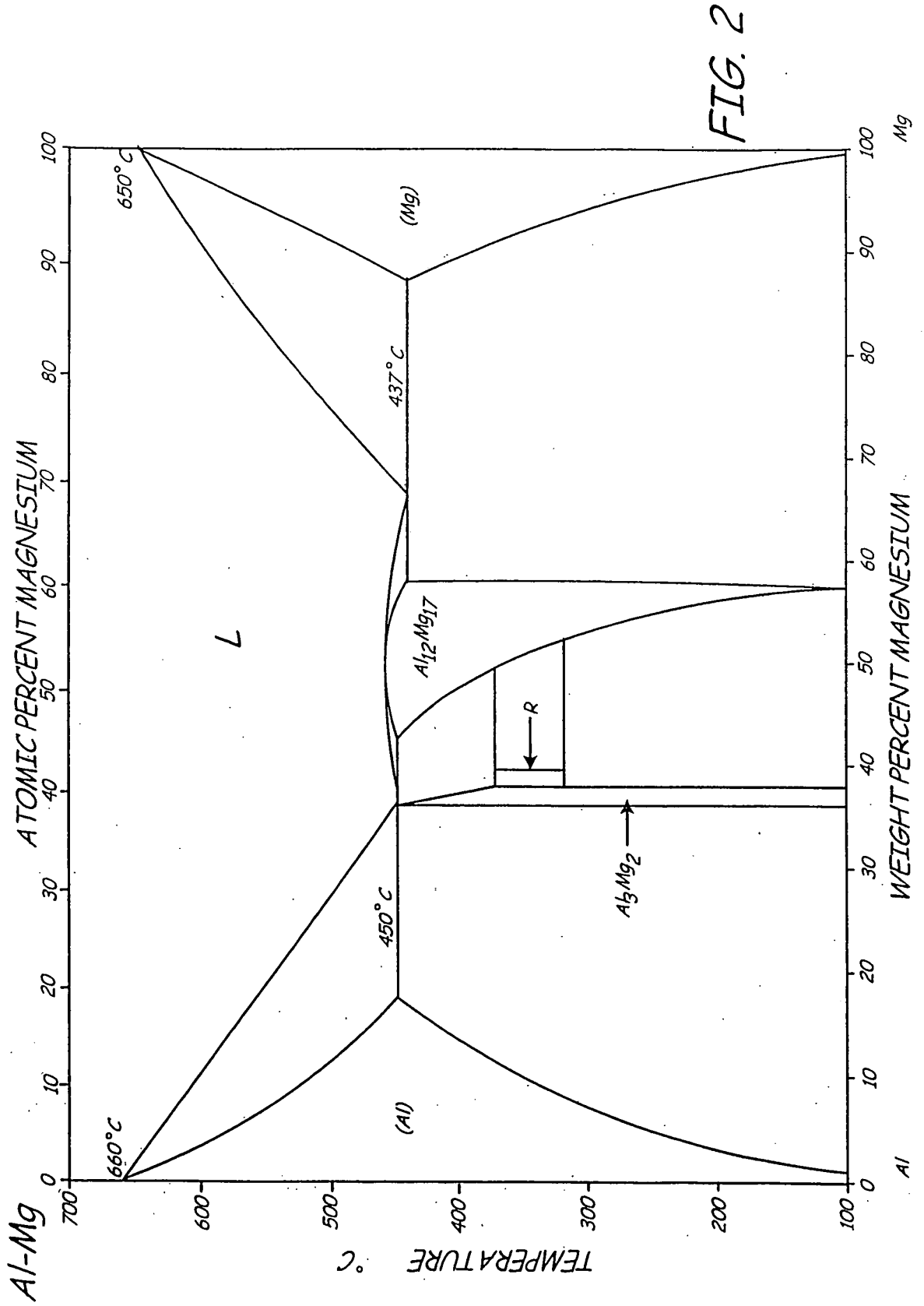
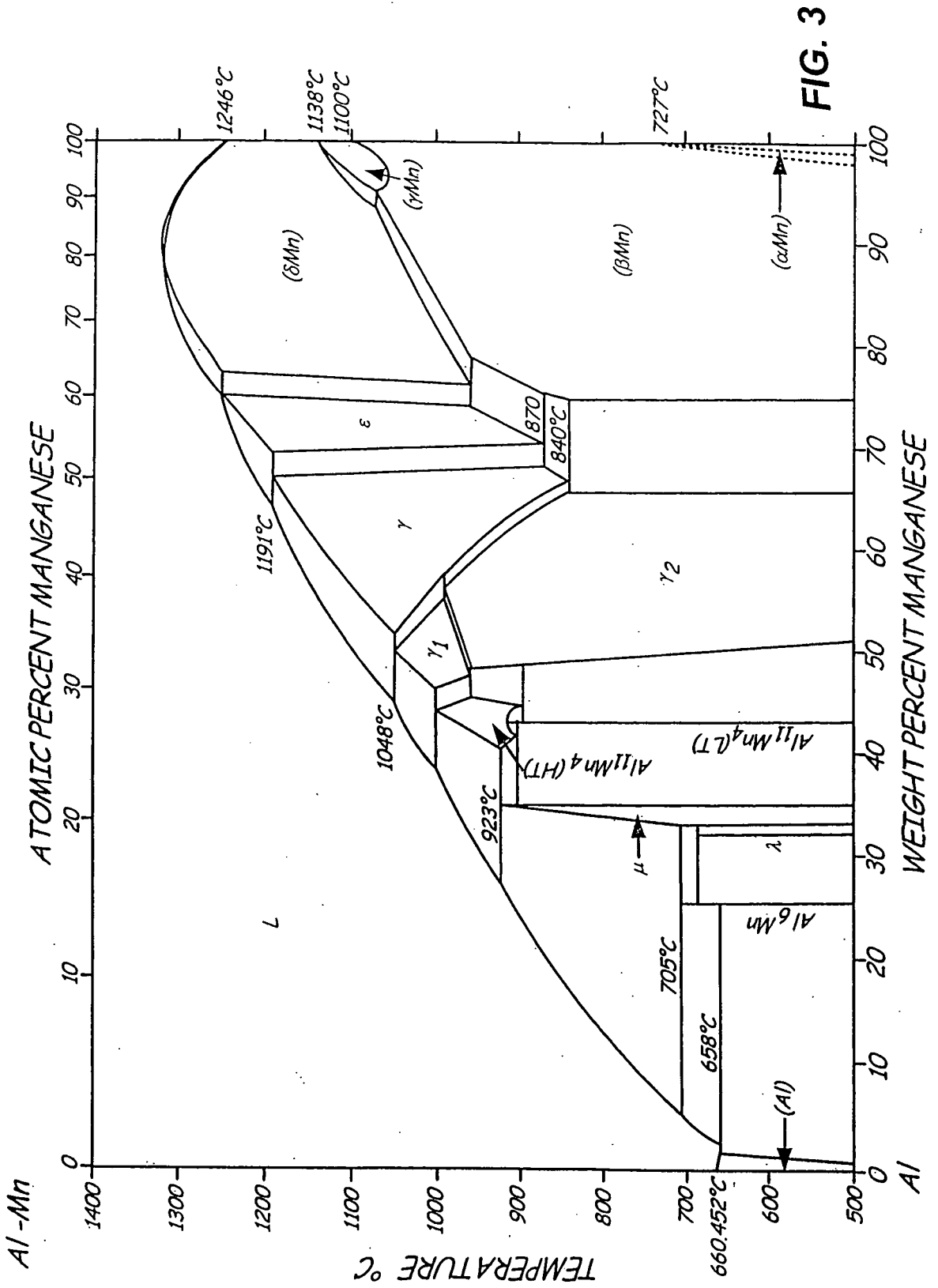


FIG. 2



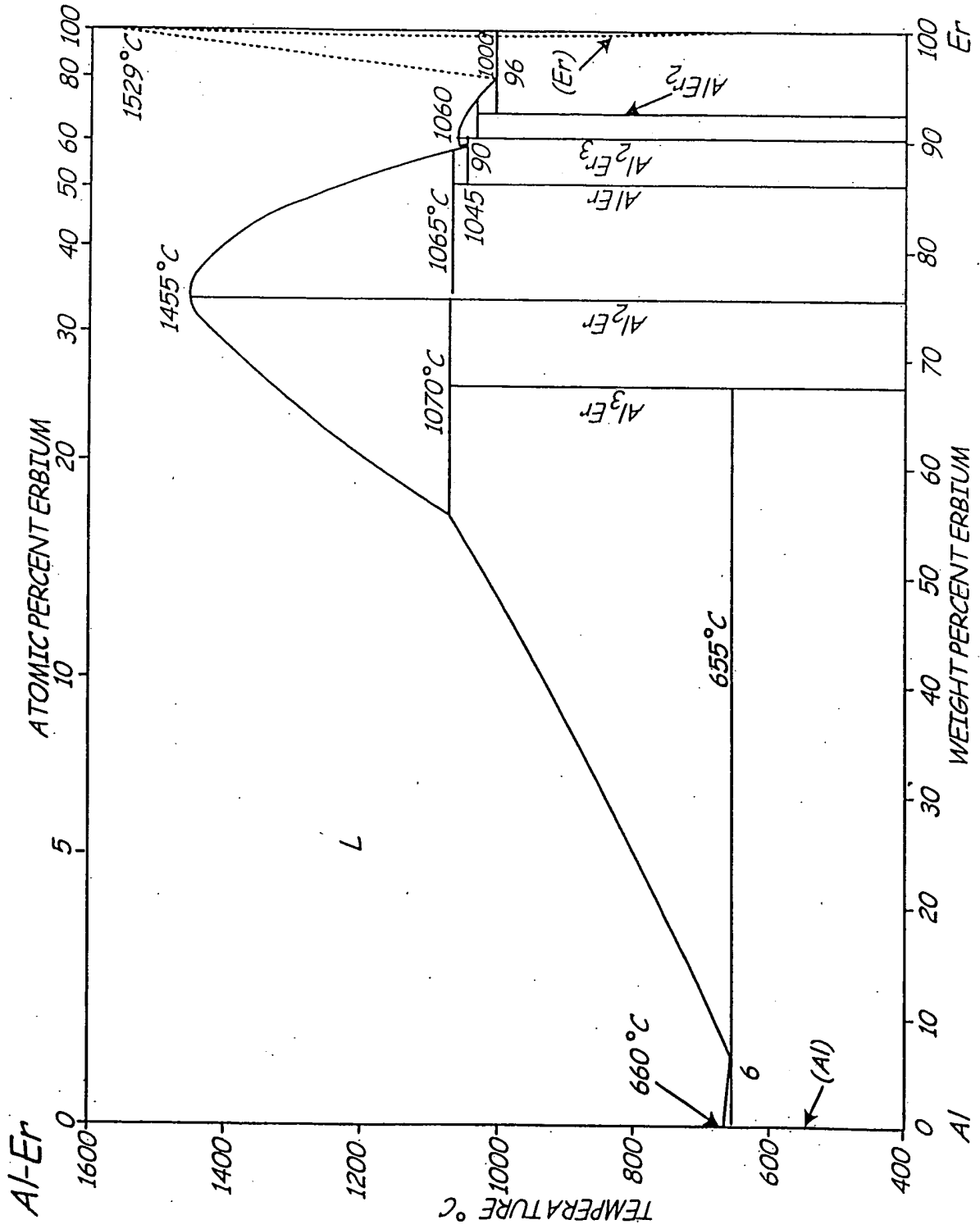
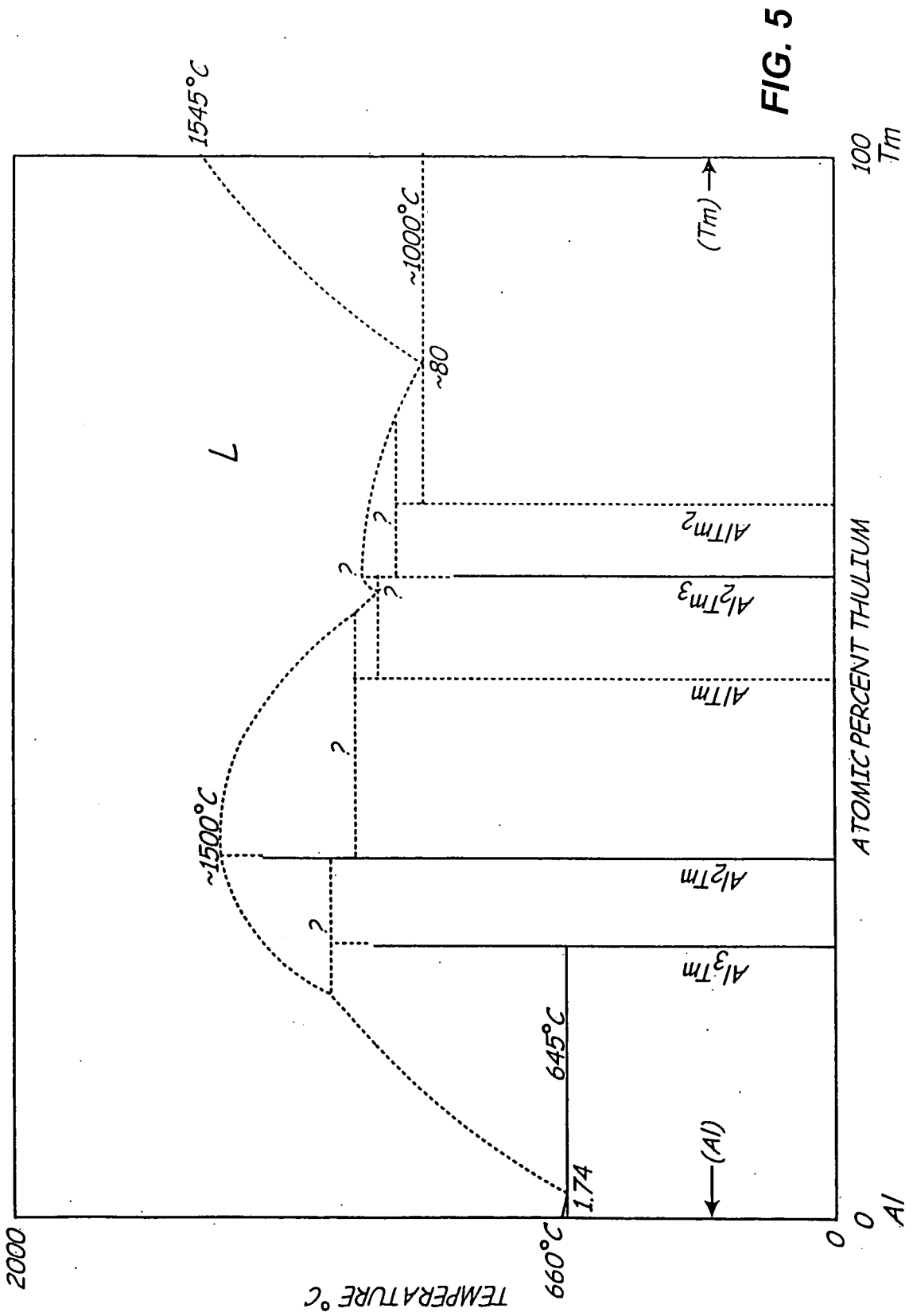


FIG. 4



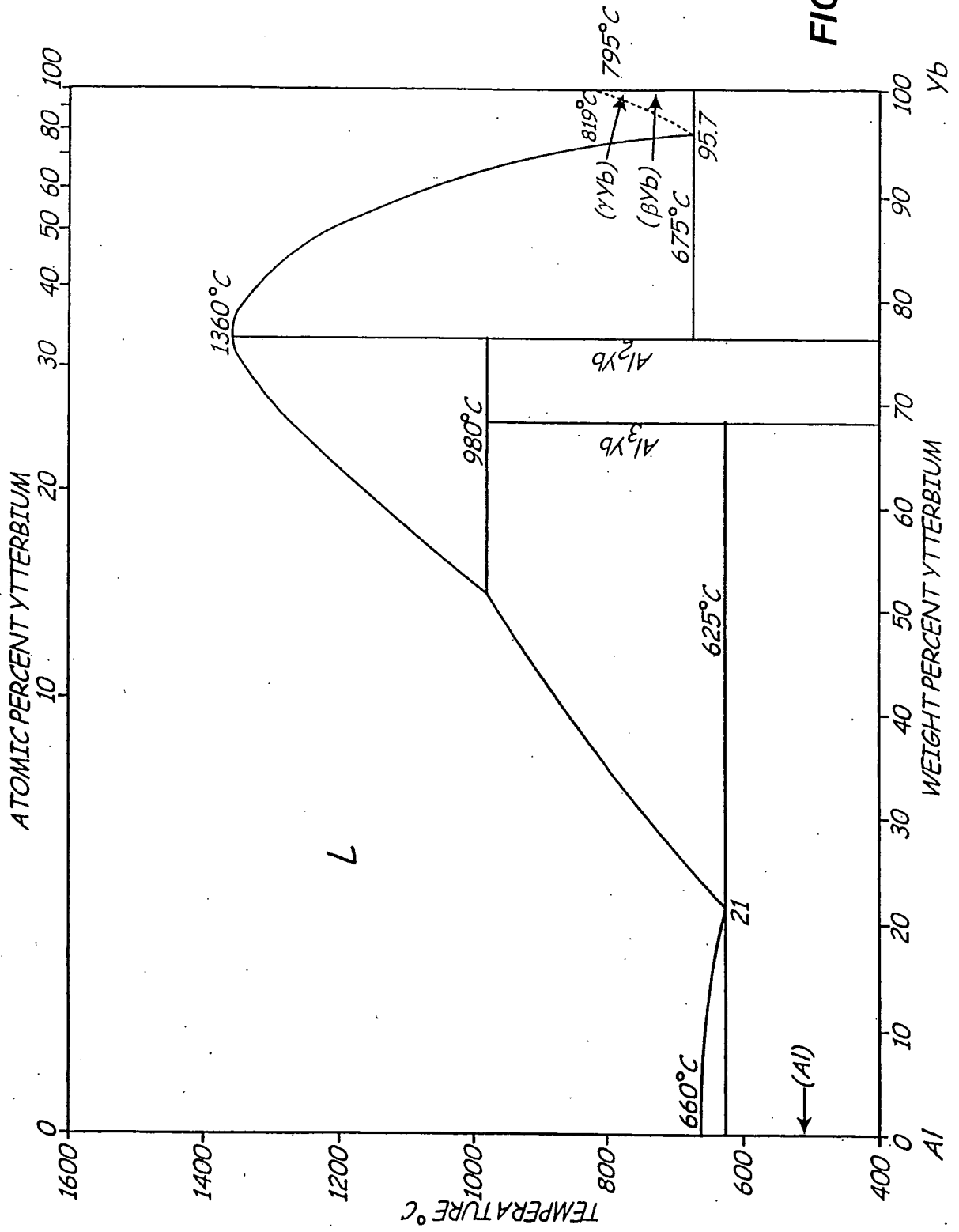


FIG. 6

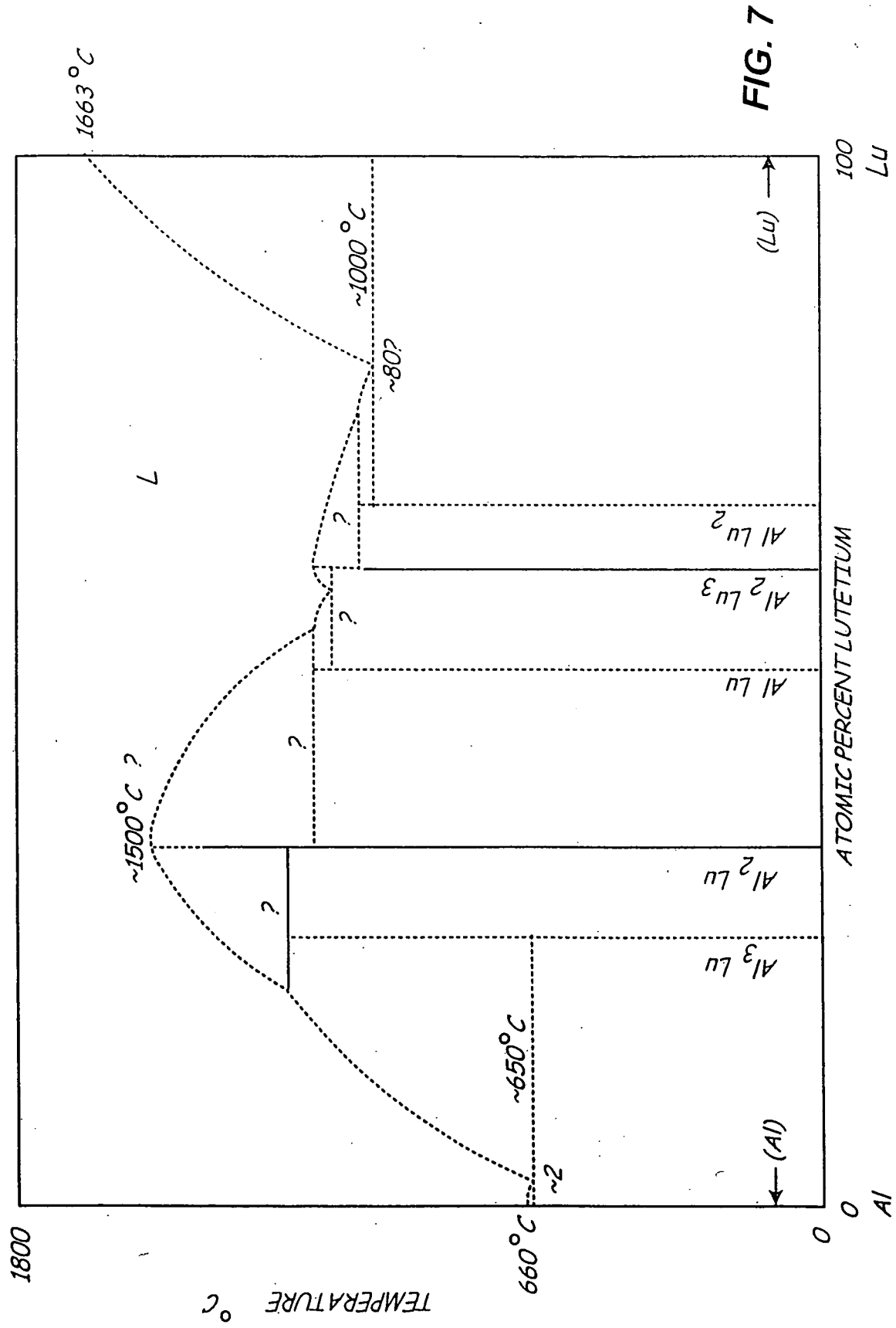


FIG. 7

**REFERENCES CITED IN THE DESCRIPTION**

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**Patent documents cited in the description**

- US 6248453 B [0005]
- US 20060269437 A [0005]
- JP 09104940 B [0007]
- US 2005013725 A [0009]

**Non-patent literature cited in the description**

- **LITYNSKA LIDIA et al.** *Experimental and theoretical characterization of Al<sub>3</sub>Sc precipitates in Al-Mg-Si-Cu-Sc-Zr alloys* [0008]
- **LITYNSKA-DOBRZYNSKA et al.** *Precipitation of phases in Al-Mg-Si-Cu alloy with Sc and Zr additions during heat treatment* [0008]