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(54) High temperature aluminium alloys

Hochtemperatur-Legierungen auf Aluminiumbasis

Alliages d' aluminium pour utilisation à haute temperature

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Description

FIELD OF THE INVENTION

[0001] The present invention relates generally to a method of making aluminum alloys, and more specifically, to aluminum alloys that are useful for applications at temperatures from -420°F (-251°C) up to 650°F (343°C).

BACKGROUND OF THE INVENTION

[0002] Aluminum alloys are used in aerospace and space applications because of their high strength, high ductility, high fracture toughness and low density. However, aluminum alloys are typically limited to use below about 250°F (121°C) because above that temperature most aluminum alloys lose their strength due to rapid coarsening of strengthening precipitates therein.

[0003] Considerable effort has been made to increase the temperature capability of aluminum alloys. Some attempts have included using 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. However, the strength of these alloys degrades at higher temperatures due to coarsening of the incoherent dispersoids. Furthermore, these alloys have lower ductility and fracture toughness than other commercially available aluminum alloys.

[0004] Other attempts have included using aluminum alloys such as Al-Mg and Al-Ti that are strengthened by incoherent oxide particles. While these alloys have promising strength at high temperatures, they have lower ductility and fracture toughness than other commercially available aluminum alloys.

[0005] Yet other attempts have included using Al-Sc based alloys that contain low volume fractions of strengthening coherent dispersoids. However, since these Al-Sc based alloys were developed to obtain improved superplasticity (which requires lower flow stress at high temperatures), they are not suitable for providing high temperature strength (which would require much higher flow stress at high temperatures) at temperatures up to about 650°F (343°C).

[0006] Still other attempts have included using Al-Sc based alloys that contain gadolinium and/or zirconium, and preferably magnesium too. While these alloys have good ductility and fracture toughness, they are only useful at temperatures up to about 573°F (300°C).

[0007] Existing aluminum alloys lack the desired strength, ductility and fracture toughness that are needed for many applications at temperatures up to about 650°F (343°C). Therefore, it would be desirable to have aluminum alloys that have the desired strength, ductility and fracture toughness that are needed for various applications at temperatures from -420°F (-251°C) up to 650°F (343°C).

[0008] EP 1471157 discloses a high-strength and high ductility aluminum alloy. RU C1 2001 144 discloses casting of an aluminum-based alloy.

SUMMARY OF THE INVENTION

[0009] Accordingly, the above-identified shortcomings of existing aluminum alloys are overcome by embodiments of the present invention, which relates to a method of making aluminum alloys that have superior strength, ductility and fracture toughness at temperatures from -420°F (-251°C) up to 650°F (343°C).

[0010] The invention provides a method according to claim 1.

[0011] Preferred embodiments of the invention are defined in the dependent claims.

[0012] Further features, aspects and advantages of the present invention will be readily apparent to those skilled in the art during the course of the following description, wherein references are made to the accompanying figures which illustrate some preferred forms of the present invention, and wherein like characters of reference designate like parts throughout the drawings.

DESCRIPTION OF THE DRAWINGS

[0013] Embodiments of the present invention are described herein below with reference to various figures, in which:

Figure 1 is a phase diagram of Al-Sc; and

Figure 2 is a graph showing strength versus temperature for a variety of aluminum alloys; and

Figure 3 is a graph showing specific strength versus temperature for a variety of materials.

DETAILED DESCRIPTION OF THE INVENTION

[0014] For the purposes of promoting an understanding of the invention, reference will now be made to some embodiments of this invention as illustrated in FIGURES 1-3 and specific language used to describe the same. The terminology used herein is for the purpose of description, not limitation. Specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a basis for teaching one skilled in the art to variously employ the present invention. Any modifications or variations in the depicted embodiments, and such further applications of the principles of the invention as illustrated herein, as would normally occur to one skilled in the art, are considered to be within the scope of this invention as claimed.

[0015] When referring to numerical ranges of values, such ranges include each and every number and/or fraction thereof at and between and the stated range minimum and maximum. For example, a range of about 0.1-1.0 weight percent element A includes all intermediate values of 0.6, 0.7 and 0.8 weight percent element A, all the way up to and including 0.98, 0.99, 0.995 and 1.0 weight percent element A, etc. This applies to all the numerical ranges of values for all elements and/or compositions discussed herein.

[0016] As used herein and throughout, "substantially free" means having no significant amount of an element or composition purposely added to the alloy composition, it being understood that trace amounts of incidental elements and/or impurities may be present in a desired end product.

[0017] This invention relates to aluminum alloys that have superior strength, ductility and fracture toughness for applications at temperatures from -420°F (-251°C) up to 650°F (343°C). These aluminum alloys comprise alloying elements that have been selected because they have low diffusion coefficients in aluminum, they have low solid solubilities in aluminum, and they can form dispersoids that have low interfacial energies with aluminum. Solid solution alloying is beneficial because it provides additional strengthening and greater work hardening capability, which results in improved failure strain and toughness. The alloys of this invention consist of aluminum, scandium, nickel, gadolinium and zirconium. These alloys comprise an aluminum solid solution matrix with a mixture of dispersoids therein. These dispersoids comprise Al_3X dispersoids having an $L1_2$ structure, where X comprises scandium and at least one of zirconium and gadolinium. These alloys also comprise dispersoids of Al_3Ni, which are different than the $L1_2$ dispersoids. Unlike many existing Al-Sc based alloys, these alloys are free of magnesium, and instead comprise nickel, which provides solid solution strengthening that is more thermally stable at high temperatures.

[0018] Aluminum alloys may comprise: (a) 0.6-2.9 weight percent scandium; (b) 1.5-25 weight percent nickel, (c) 0.4-20 weight percent gadolinium, (d) 0.4-2.9 weight percent zirconium, and the balance aluminum. In the balance that is aluminum, there may also be some minor amounts of impurities or other materials and/or elements that do not materially affect the basic and novel characteristics of the alloy.

[0019] Exemplary aluminum alloys of the invention include, but are not limited to (in weight percent):

Al-(6-10)Ni-(1-2.9)Sc-(6-10)Gd-(0.5-2.9)Zr;
and more specifically
Al-8.4Ni-2.15Sc-8.8Gd-2.5Zr;
Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr.

[0020] The following aluminum alloys do not fall within the scope of the invention:

Al-(6-10)Ni-(1-2.9)Sc-(6-10)Gd-(1-4)Y;
Al-(6-10)Ni-(1-2.9)Sc-(2-6)Gd-(4-8)Y;
Al-(6-10)Ni-(1-2.9)Sc-(6-12)Hf-(0.5-2.9)Zr;
Al-(6-10)Ni-(1-2.9)Sc-(6-12)Hf-(3-7)Gd;
Al-(6-10)Ni-(1-2.9)Sc-(6-12)Hf-(2-6)Y;
Al-(6-10)Ni-(1-2.9)Sc-(4-9)Y-(0.5-2.9)Zr;
Al-(6-10)Ni-(1-2.9)Sc-(1-6)Nb-(0.5-2.9)Zr;
Al-(6-10)Ni-(1-2.9)Sc-(6-12)Hf-(1-6)Nb;
Al-(6-10)Ni-(1-2.9)Sc-(6-12)Hf-(1-5)V;
Al-(6-10)Ni-(1-2.9)Sc-(1-6)Nb-(1-5)V; and
Al-(6-10)Ni-(1-2.9)Sc-(0.5-2.9)Zr-(1-5)V.
Al-8.4Ni-2.15Sc-4.1Gd-5.4Y;
Al-8.4Ni-2.15Sc-8.5Gd-2.5Y;
Al-8.4Ni-2.15Sc-11.5Hf-1.5Zr;
Al-8.4Ni-2.15Sc-9.8Hf-1.5Zr;
Al-8.4Ni-2.15Sc-9.0Hf-4.5Gd;
Al-8.4Ni-2.15Sc-8.5Hf-3.0Y;

Al-8.4Ni-2.15Sc-6.5Y-1.5Zr;
Al-8.4Ni-2.15Sc-5.0Nb-2.1Zr;
Al-8.4Ni-2.15Sc-9.5Hf-2.5Nb;
Al-8.4Ni-2.15Sc-8.0Hf-2.0V;
Al-8.4Ni-2.15Sc-2.5Nb-3.2V; and
Al-8.4Ni-2.15Sc-2.5Zr-3.2V.

[0021] Scandium is a potent strengthener in aluminum alloys, and has low diffusivity and low solubility in aluminum. Scandium forms Al_3Sc dispersoids in the aluminum. The Al_3Sc dispersoids have an $L1_2$ structure that is an ordered face centered cubic structure with scandium atoms located at the corners and aluminum atoms located on the cube faces. The Al_3Sc dispersoids are fine and coherent with the aluminum matrix. The lattice parameters of aluminum and Al_3Sc are very close, 0.405nm and 0.410nm respectively, indicating that there is minimal or no driving force for causing growth of the Al_3Sc dispersoids. This low interfacial energy makes the Al_3Sc dispersoids thermally stable and resistant to coarsening up to temperatures as high as about 842°F (450°C). In the alloys of this invention, these Al_3Sc dispersoids are made stronger and more resistant to coarsening at elevated temperatures by adding suitable alloying elements, such as gadolinium, and zirconium.

[0022] Gadolinium forms Al_3Gd dispersoids in the aluminum that are stable up to temperatures as high as about 842°F (450°C) due to their low diffusivity in aluminum. The Al_3Gd dispersoids have a DO_{19} structure in the equilibrium condition. Despite its large atomic size, gadolinium has fairly high solubility in Al_3Sc. Gadolinium can substitute with scandium in Al_3Sc, thereby forming an ordered $L1_2$ phase of $Al_3(Sc_x,Gd_{1-x})$ dispersoids, which results in improved thermal and structural stability.

[0023] Zirconium forms Al_3Zr dispersoids in the aluminum that have an $L1_2$ structure in the metastable condition and a DO_{23} structure in the equilibrium condition. The Al_3Zr dispersoids have a low diffusion coefficient, which makes them thermally stable and highly resistant to coarsening. Similarity in the nature of Al_3Zr and Al_3Sc dispersoids allow at least partial intersolubility of these phases, thereby resulting in an ordered $L1_2$ $Al_3(Sc_x,Zr_{1-x})$ phase. Substituting zirconium for scandium in the Al_3Sc dispersoids allows stronger and more thermally stable $L1_2$ $Al_3(Sc_x,Zr_{1-x})$ dispersoids to form.

[0024] The thermal and structural stability of the Al_3Sc dispersoids can be increased by adding both gadolinium and zirconium. The Al-Sc-Gd-Zr alloy forms an ordered $L1_2$ $Al_3(Sc,Gd,Zr)$ phase having improved thermal and structural stability, which is believed to be due to the reduced lattice mismatch between the aluminum matrix and the dispersoids. Furthermore, the modified $Al_3(Sc,Gd,Zr)$ dispersoids are stronger than the Al_3Sc dispersoids, thereby improving the mechanical properties of the alloy at temperatures from -420°F (-251°C) up to 650°F (343°C).

[0025] Nickel is added to derive dispersion and/or solid solution strengthening thermally stable at high temperatures. Nickel is added because it forms thermally stable spherical Al_3Ni dispersoids, and in powder form nickel can be undercooled to relatively large levels (as compared to iron, chromium, manganese and cobalt) by controlling the powder processing parameters.

[0026] Nickel forms an eutectic with aluminum, resulting in a mixture of a solid solution of nickel in aluminum and Al_3Ni dispersoids. Nickel is added to the alloys of this invention for two reasons. First, solid solution strengthening is derived from the nickel. Second, the Al_3Ni dispersoids help dispersion strengthen the alloy. The aluminum solid solution and Al_3Ni dispersoids are thermally stable, which contributes to the high temperature strengthening of the alloys. The solid solubility of nickel in aluminum can be increased significantly by utilizing rapid solidification processing.

[0027] The amount of scandium present in the alloys of this invention varies from 0.6 to 2.9 weight percent, depending on the processing technique used for producing the material. As shown in Figure 1, the phase diagram of Al-Sc indicates an eutectic reaction at about 0.5 weight percent scandium at about 1219°F (659°C), resulting in a solid solution of scandium in aluminum and Al_3Sc dispersoids. The phase diagram also shows a steep liquidus for hypereutectic compositions (i.e., compositions comprising greater than about 0.5 weight percent scandium). This suggests that casting techniques can be used for scandium compositions comprising only about 0.5 weight percent scandium or less. For hypereutectic compositions, rapid solidification techniques such as melt spinning, atomization, spray deposition, vacuum plasma spraying, cold spraying, cryomilling, high energy ball milling, or other techniques utilizing higher cooling rates may need to be used to process the material. The amount of scandium that can be taken in supersaturation also depends upon the cooling rate. Ideally, all the scandium would be kept in solution to avoid the formation of primary particles, which are usually large in size and therefore, are not considered to be beneficial for mechanical properties. The upper limit of 2.9 weight percent scandium was selected because atomization, the most common processing technique, can provide complete supersaturation of scandium in aluminum only up to about 3 weight percent scandium.

[0028] The amount of gadolinium present in the alloys of this invention varies from 0.4 to 20 weight percent. The amount of gadolinium present depends on the solubility of gadolinium in the Al_3Sc dispersoids. In embodiments, the atomic percents of gadolinium and scandium may be equivalent so that gadolinium can substitute up to about 50% in $Al_3(Sc_x,Gd_{1-x})$ dispersoids. Gadolinium also forms a solid solution of gadolinium in aluminum. Since Al-Gd forms an eutectic at about 23 weight percent gadolinium, slower cooling rate processing (i.e., casting) may be used for processing such alloys. However, rapid solidification techniques are preferred in some embodiments to increase the supersaturation of gadolinium and decrease the size of the dispersoids, which thereby provides higher strength to the alloy.

[0029] The amount of zirconium present in the alloys of this invention varies from 0.4 to 2.9 weight percent. In these alloys, zirconium is substituted for scandium in the Al_3Sc dispersoids, forming $Al_3(Sc_x,Zr_{1-x})$, which controls the coarsening kinetics of the alloys. Since zirconium has high solubility in the Al_3Sc dispersoids, zirconium can be substituted up to about 50% in the $Al_3(Sc_x,Zr_{1-x})$ dispersoids. Zirconium also forms a solid solution of zirconium in aluminum. While casting may be used with small zirconium additions, rapid solidification is preferred for alloys having larger zirconium additions. However, rapid solidification techniques may be preferred in some embodiments to increase the supersaturation of zirconium and decrease the size of the dispersoids, which thereby provides higher strength to the alloy. The upper limit of about 2.9 weight percent zirconium was selected because atomization, the most common processing technique, can provide complete supersaturation of zirconium in aluminum only up to about 3 weight percent zirconium.

[0030] The amount of nickel present in the alloys of this invention varies from 1.5 to 25 weight percent. The amount of nickel present depends on the solubility of nickel in aluminum. Nickel has limited solubility in aluminum, but its solubility can be extended significantly by utilizing rapid solidification techniques. The Al-Ni system forms an eutectic with aluminum, resulting in Al_3Ni dispersoids in a solid solution of nickel in aluminum. Slower cooling rate techniques (i.e., casting) may be used for processing alloys having nickel additions. However, rapid solidification techniques are preferred in some embodiments to increase the supersaturation of nickel and decrease the size of the dispersoids, which thereby provides higher strength to the alloy. While up to 25 weight percent nickel may be used in these alloys, in embodiments, only up to 15 weight percent nickel may be desired due to the possible extension of the solid solubility of nickel in aluminum by rapid solidification techniques.

[0031] In embodiments, there may be 10-40 volume percent of fine Al_3X based dispersoids present in order to provide the desired high strength at temperatures up to about 650°F (343°C). Some embodiments comprise 15-20 volume percent of fine Al_3X based dispersoids. However, depending upon the size of the dispersoids, higher or lower volume percents of Al_3X based dispersoids may be present to provide balanced strength and ductility at temperatures up to about 650°F (343°C).

[0032] These aluminum alloys may be made in various forms (i.e., ribbon, flake, powder, etc.) by any rapid solidification technique that can provide supersaturation of elements, such as, but not limited to, melt spinning, splat quenching, spray deposition, vacuum plasma spraying, cold spraying, laser melting, mechanical alloying, ball milling (i.e., at room temperature), cryomilling (i.e., in a liquid nitrogen environment), spin forming, or atomization. Any processing technique utilizing cooling rates equivalent to or higher than 10^3°C/second is considered to be a rapid solidification technique for these alloys. Therefore, the minimum desired cooling rate for the processing of these alloys is 10^3°C/second, although higher cooling rates may be necessary for alloys having larger amounts of alloying additions.

[0033] Atomization is the preferred technique for creating embodiments of the alloys of the invention. Atomization is one of the most common rapid solidification techniques used to produce large volumes of powder. The cooling rate experienced during atomization depends on the powder size and usually varies from 10^3 to 10^5°C/second. Helium gas atomization is often desirable because helium gas provides higher heat transfer coefficients, which leads to higher cooling rates in the powder. Fine size powders (i.e., about -325 mesh) may be desirable so as to achieve maximum supersaturation of alloying elements that can precipitate out during powder processing.

[0034] Cryomilling may be the preferred technique for creating other embodiments of aluminum alloys. Cryomilling introduces oxynitride particles in the powder that can provide additional strengthening to the alloy at high temperatures by increasing the threshold stress for dislocation climb. Additionally, the nitride particles, when located on grain boundaries, can reduce the grain boundary sliding in the alloy by pinning the dislocation, which results in reduced dislocation mobility in the grain boundary.

[0035] Once the alloy composition (i.e., ribbon, flake, powder, etc.) is created, and after suitable vacuum degassing, the powder, ribbon, flake, etc. can be compacted in any suitable manner, such as, for example, by vacuum hot pressing or blind die compaction (where compaction occurs in both by shear deformation) or by hot isostatic pressing (where compaction occurs by diffusional creep).

[0036] After compaction, the alloy may be extruded, forged, or rolled to impart deformation thereto, which is important for achieving the best mechanical properties in the alloy. In embodiments, extrusion ratios ranging from about 10:1 to about 22:1 may be desired. In some embodiments, low extrusion ratios (i.e., about 2:1 to about 9:1) may be useful. Hot vacuum degassing, vacuum hot pressing and extrusion may be carried out at any suitable temperature, such as, for example, at 572-842°F (300-450°C).

EXAMPLES

[0037] Various embodiments of the following alloy compositions (in weight percent) were produced using various powder metallurgy processes: Al-8.4Ni-2.15Sc-8.8Gd-2.5Zr, Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr and Al-8.4Ni-2.15Sc-4.1Gd-5.4Y. The powder metallurgy processes used for producing these alloys consisted of ingot fabrication, inert helium gas atomization, hot vacuum degassing, vacuum hot pressing, and extrusion. Alloying elements were mixed together and melted in an argon atmosphere at 2100-2300°F (1149-1260°C) for 15-60 minutes to form ingots of the above-noted compositions, each having very low oxygen content. The ingots were then further melted in an argon atmosphere at 2400-2600°F (1316-1427°C) for 15-60 minutes, and were then atomized via helium gas atomization to form spherical powders that also had very low oxygen content. The powders were then sieved to about -325 mesh. Thereafter, the powders were hot vacuum degassed at 650-750°F (343-399°C) for 4-15 hours to remove moisture and undesired gases from the powders. Next, the powders were compacted in a unidirectional vacuum hot press at 650-750°F (343-399°C) for 1-5 hours to create billets. The billets were then extruded at 650-750°F (343-399°C) for 5-30 minutes using extrusion ratios ranging from about 5:1 to about 25:1 to produce round bars of different sizes. Some non-limiting embodiments of each alloy were produced according to the processing parameters shown in Table I below.

TABLE I

	Al-8.4Ni-2.15Sc-8.8Gd-2.5Zr	Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr	Al-8.4Ni-2.15Sc-4.1 Gd-5.4Y
Ingot fabrication	~ 2200°F (1204°C) ~ 30 minutes	~ 2200°F (1204°C) ~ 30 minutes	~ 2200°F (1204°C) ~ 30 minutes
Helium gas atomization	~ 2500°F (1371°C) ~ 30 minutes	~ 2500°F (1371°C) ~ 30 minutes	~ 2500°F (1371°C) ~ 30 minutes
Hot vacuum degassing	~ 750°F (399°C) ~ 4 hours	~ 700°F (371°C) ~ 15 hours	~ 700°F (371°C) ~ 15 hours
Vacuum hot pressing	~ 650°F (343°C) ~ 1 hour	~ 700°F (371°C) ~ 5 hours	~ 700°F (371°C) ~ 5 hours
Extrusion	~ 700°F (371°C) ~ 30 minutes	~ 750°F (399°C) ~ 5 minutes	~ 750°F (399°C) ~ 5 minutes
Extrusion ratios	22:1	10:1 and 22:1	10:1 and 22:1

[0038] Various properties (i.e., ultimate tensile strength, yield strength, percent elongation, percent reduction in area, and modulus) of these round bars were then tested in air. These same properties were also tested for some of the Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr and Al-8.4Ni-2.15Sc-4.1Gd-5.4Y bars in high pressure (i.e., about 5 ksi (34.5 MPa)) gaseous hydrogen. The Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr and Al-8.4Ni-2.15Sc-4.1Gd-5.4Y alloys showed good strength and ductility in high pressure gaseous hydrogen, indicating that there is no hydrogen embrittlement of these alloys in such environments.

[0039] The Al-8.4Ni-2.15Sc-8.8Gd-2.5Zr, Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr and Al-8.4Ni-2.15Sc-4.1Gd-5.4Y alloys all showed very high strengths in air for a range of temperatures up to about 650°F (343°C), as seen in Figures 2 and 3. As can be seen in Figure 2, the Al-8.4Ni-2.15Sc-8.8Gd-2.5Zr, Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr and Al-8.4Ni-2.15Sc-4.1Gd-5.4Y alloys, 10, 11, 12 respectively, are all significantly stronger than two commercial aluminum alloys (7075 and 6061) 13, 14 respectively. The Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr and Al-8.4Ni-2.15Sc-4.1Gd-5.4Y alloys, 11, 12, had lower strengths than the Al-8.4Ni-2.15Sc-8.8Gd-2.5Zr alloy, 10, because they were processed at higher temperatures for longer amounts of time, as shown in Table I. This suggests that the alloys of this invention could be used to make stronger, lighter weight aerospace and space components.

[0040] Furthermore, the alloys of this invention also have a much higher specific strength (strength/density) in air than various other non-aluminum alloys, such as those materials currently utilized in rocket engines, as shown in Figure 3. As can be seen, the specific strengths (strength/density) of the Al-8.4Ni-2.15Sc-8.8Gd-2.5Zr, Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr and Al-8.4Ni-2.15Sc-4.1Gd-5.4Y alloys, 10, 11, 12 respectively, are higher than nickel based superalloy IN625 18, nitronic 40 steel 20, and 347 stainless steel 22, at least up to temperatures of about 425°F (218°C). It is believed that the processing of the Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr and Al-8.4Ni-2.15Sc-4.1Gd-5.4Y alloys, 11, 12, can be further optimized to provide even greater strengths at temperatures up to about 650°F (343°C). Regardless, these results suggest that the alloys of this invention could be used to make significantly lighter weight rocket and aircraft structures, which would improve the thrust-to-weight ratio of the engines and reduce the cost for flights.

[0041] The alloys of the present invention can be used in monolithic form, or can contain continuous or discontinuous reinforcement materials (i.e., second phases) to produce metal-matrix composites. Suitable reinforcement materials include, but are not limited to, oxides, carbides, nitrides, oxynitrides, oxycarbonitrides, silicides, borides, boron, graphite, ferrous alloys, tungsten, titanium and/or mixtures thereof. Specific reinforcement materials include, but are not limited to, SiC, Si_3N_4, Al_2O_3, B_4C, Y_2O_3, $MgAl_2O_4$, TiC, TiB_2 and/or mixtures thereof. These reinforcement materials may be present in volume fractions of up to 50 volume percent, more preferably 0.5-50 volume percent, and even more preferably 0.5-20 volume percent.

[0042] The aluminum alloys of this invention may be used for various rocket and aircraft applications, such as for, but not limited to, structural jackets, turbo pump housings, turbine rotors, turbine rotor housings, impellers, valves, valve housings, injectors, nozzles, brackets, ducts/plumbing, and other structural components for rocket engines; and air inlet housings, stator assemblies, gearboxes, bearing housings, carbon seal housings, domes, covers, vanes and stators for jet engines. These alloys can also be used for other applications in jet engines, rocket engines and automobiles requiring high strengths at temperatures from -420°F (-251°C) up to 650°F (343°C).

[0043] Various embodiments of this invention have been described in fulfillment of the various needs that the invention meets. It should be recognized that these embodiments are merely illustrative of the principles of various embodiments of the present invention. Numerous modifications and adaptations thereof will be apparent to those skilled in the art without departing from the scope of the present invention. Thus, it is intended that the present invention cover all suitable modifications and variations as come within the scope of the appended claims.

Claims

1. A method of making an aluminum alloy comprising: providing an aluminum alloy comprising:

(a) 0.6-2.9 weight percent scandium;
(b) 1.5-25 weight percent nickel;
(c) 0.4-20 weight percent gadolinium;
(d) 0.4-2.9 weight percent zirconium; and
(e) the balance aluminum;

the method comprising the steps of: producing the alloy by a rapid solidification technique utilizing a cooling rate of at least 10^3 °C/second or higher, wherein the rapid solidification technique comprises at least the following steps:

creating an ingot having a predetermined composition;
melting the ingot;
atomizing the melted ingot to form a powder;
degassing the powder;
compacting the powder to create a billet;
hot working the billet into a predetermined form;
wherein the compacting step comprises vacuum hot pressing the powder at 343-399°C for 1-5 hours.

2. The method of claim 1, wherein the alloy comprises an aluminum solid solution matrix and a dispersion of Al_3Ni and Al_3X, the Al_3X having an $L1_2$ structure where X comprises scandium and at least one of gadolinium, zirconium.

3. The method of claim 1 or 2, wherein the alloy is free of magnesium.

4. The method of any preceding claim, wherein the alloy is capable of being used at temperatures from -420°F (-251 °C) up to 650°F (343°C).

5. A method of making an aircraft component, a rocket component, and an automobile component; the method comprising using the alloy made by the method of any preceding claim.

6. The method of claim 5, wherein the rocket component comprises at least one of a structural jacket, a turbo pump housing, a turbine rotor, a turbine rotor housing, an impeller, a valve, a valve housing, an injector, a nozzle, a bracket, a duct, a plumbing component, and a structural rocket component.

7. The method of claim 5, wherein the aircraft component comprises at least one of an air inlet housing, a stator assembly, a gearbox, a bearing housing, a carbon seal housing, a dome, a cover, a vane, and a stator.

8. The method of any preceding claim, wherein the alloy consists of:

(a) 1-2.9 weight percent scandium;

(b) 6-10 weight percent nickel;
(c) 2-10 weight percent gadolinium,
(d) 0.5-2.9 weight percent zirconium,
(e) the balance aluminum plus unavoidable impurities.

9. The method of claim 8, wherein the alloy consists of:

(a) 2.15 weight percent scandium;
(b) 8.4 weight percent nickel;
(c) 4.1-8.8 weight percent gadolinium,
(d) 1.5-2.5 weight percent zirconium,
(e) the balance aluminum plus unavoidable impurities.

10. The method as claimed in any of claims 1 to 7, wherein the alloy consists of one of the following compositions, in weight percent:

Al-(6-10)Ni-(1-2.9)Sc-(6-10)Gd-(0.5-2.9)Zr; and
Al-8.4Ni-2.15Sc-8.8Gd-1.5Zr.

11. The method as claimed in claim 10, wherein the alloy consists of the following composition, in weight percent: Al-8.4Ni-2.15Sc-8.8Gd-2.5Zr.

12. The method of claim 11, wherein the alloy comprises an aluminum solid solution matrix, a plurality of $Al_3(Sc,Gd,Zr)$ dispersoids having an $L1_2$ structure, and a plurality of Al_3Ni dispersoids.

13. The method of claim 11, wherein the alloy further comprises up to 50 volume percent of a reinforcing second phase.

14. The method of claim 13, wherein the reinforcing second phase comprises at least one of: an oxide, a carbide, a nitride, an oxynitride, an oxycarbonitride, a silicide, a boride, a ferrous alloy, boron, graphite, tungsten, titanium, SiC, Si_3N_4, Al_2O_3, B_4C, Y_2O_3, $MgAl_2O_4$, TiC and TiB_2.

15. The method of claim 1, wherein the rapid solidification technique comprises at least one of: melt spinning, splat quenching, atomization, spray deposition, vacuum plasma spraying, cold spraying, laser melting, mechanical alloying, cryomilling, spin forming, and ball milling.

16. The method of claim 1, wherein the creating step occurs in an argon atmosphere at 1149-1260°C for 15-60 minutes.

17. The method of claim 1 or 16, wherein the melting step occurs in an argon atmosphere at 1316-1427°C for 15-60 minutes.

18. The method of claim 1, 16 or 17, wherein the degassing step comprises hot vacuum degassing the powder at 343-399°C for 4-15 hours.

19. The method of any of claims 1 or 16 to 18, wherein the hot working step occurs at 343-399°C for 5-30 minutes.

Patentansprüche

1. Verfahren zum Herstellen einer Aluminiumlegierung, umfassend: Bereitstellen einer Aluminiumlegierung, die Folgendes umfasst:

(a) 0,6-2,9 Gewichtsprozent Scandium;
(b) 1,5-25 Gewichtsprozent Nickel;
(c) 0,4-20 Gewichtsprozent Gadolinium;
(d) 0,4-2,9 Gewichtsprozent Zirconium; und
(e) Rest Aluminium;

wobei das Verfahren die folgenden Schritte umfasst: Herstellen der Legierung durch ein Schnellverfestigungsverfahren unter Verwendung einer Kühlgeschwindigkeit von mindestens 10^3 °C/Sekunde oder höher, wobei das Schnellverfestigungsverfahren mindestens die folgenden Schritte umfasst:

Erzeugen eines Rohblockes, der eine vorbestimmte Zusammensetzung aufweist;
Schmelzen des Rohblocks;
Zerstäuben des geschmolzenen Rohblocks, um ein Pulver zu bilden;
Entgasen des Pulvers;
Zusammenpressen des Pulvers, um einen Strang zu erzeugen;
Warmumformen des Strangs in eine vorgegebene Form;
wobei der Schritt des Zusammenpressens das Vakuumwarmpressen des Pulvers bei 343 -399 °C für 1-5 Stunden umfasst.

2. Verfahren nach Anspruch 1, wobei die Legierung eine Aluminium-Mischkristallmatrix und eine Dispersion von Al_3Ni und Al_3X umfasst, wobei das Al_3X eine $L1_2$-Struktur aufweist, wobei X Scandium und mindestens eines aus Gadolinium, Zirconium umfasst.

3. Verfahren nach Anspruch 1 oder 2, wobei die Legierung frei von Magnesium ist.

4. Verfahren nach einem der vorstehenden Ansprüche, wobei die Legierung bei Temperaturen von -420 °F (-251 °C) bis zu 650 °F (343 °C) verwendet werden kann.

5. Verfahren zum Herstellen einer Komponente eines Luftfahrzeugs, einer Komponente einer Rakete und einer Komponente eines Kraftfahrzeugs; wobei das Verfahren das Verwenden der Legierung umfasst, die durch das Verfahren nach einem der vorstehenden Ansprüche hergestellt wurde.

6. Verfahren nach Anspruch 5, wobei die Raketenkomponente mindestens eines aus einer strukturellen Umhüllung, einem Turbopumpengehäuse, einem Turbinenrotor, einem Turbinenrotorgehäuse, einem Läufer, einem Ventil, einem Ventilgehäuse, einer Einspritzeinrichtung, einer Düse, einer Halterung, einem Kanal, einer Rohrleitungskomponente, und einer Konstruktionskomponente der Rakete umfasst.

7. Verfahren nach Anspruch 5, wobei die Komponente eines Luftfahrzeugs mindestens eines aus einem Lufteinlassgehäuse, einer Statoranordnung, einem Getriebekasten, einem Lagergehäuse, einem Carbon-Dichtungsgehäuse, einer Kuppel, einer Abdeckung, einer Leitschaufel und einem Stator umfasst.

8. Verfahren nach einem der vorstehenden Ansprüche, wobei die Legierung aus Folgendem besteht:

(a) 1-2,9 Gewichtsprozent Scandium;
(b) 6-10 Gewichtsprozent Nickel;
(c) 2-10 Gewichtsprozent Gadolinium,
(d) 0,5-2,9 Gewichtsprozent Zirconium,
(e) Rest Aluminium plus unvermeidbare Verunreinigungen.

9. Verfahren nach Anspruch 8, wobei die Legierung aus Folgendem besteht:

(a) 2,15 Gewichtsprozent Scandium;
(b) 8,4 Gewichtsprozent Nickel;
(c) 4,1-8,8 Gewichtsprozent Gadolinium,
(d) 1,5-2,5 Gewichtsprozent Zirconium,
(e) Rest Aluminium plus unvermeidbare Verunreinigungen.

10. Verfahren nach einem der Ansprüche 1 bis 7, wobei die Legierung aus einer der folgenden Zusammensetzungen besteht, in Gewichtsprozent:

Al-(6-10)Ni-(1-2,9)Sc-(6-10)Gd-(0,5-2,9)Zr; und
Al-8,4Ni-2,15Sc-8,8Gd-1,5Zr.

11. Verfahren nach Anspruch 10, wobei die Legierung aus der folgenden Zusammensetzung besteht, in Gewichtsprozent:

Al-8,4Ni-2,15Sc-8,8Gd-2,5Zr.

12. Verfahren nach Anspruch 11, wobei die Legierung eine Aluminium-Mischkristallmatrix umfasst, wobei eine Vielzahl von $Al_3(Sc,Gd,Zr)$-Dispersoiden eine $L1_2$-Struktur aufweist, und eine Vielzahl von Al_3Ni-Dispersoiden.

13. Verfahren nach Anspruch 11, wobei die Legierung ferner bis zu 50 Volumenprozent einer verstärkenden zweiten Phase umfasst.

14. Verfahren nach Anspruch 13, wobei die verstärkende zweite Phase mindestens eines aus Folgendem umfasst: ein Oxid, ein Carbid, ein Nitrid, ein Oxynitrid, ein Oxycarbonitrid, ein Silicid, ein Borid, eine Eisenlegierung, Boron, Graphit, Wolfram, Titanium, SiC, Si_3N_4, Al_2O_3, B_4C, Y_2O_3, $MgAl_2O_4$, TiC und TiB_2.

15. Verfahren nach Anspruch 1, wobei das Schnellverfestigungsverfahren mindestens eines aus Folgenden umfasst: Schmelzspinnen, Abschrecken aus der Schmelze, Zerstäubung, Sprühkompaktieren, Vakuum-Plasmaspritzen, Kaltspritzen, Laserschmelzen, mechanisches Legieren, kryogenes Mahlen, Drückwalzen und Kugelmahlen.

16. Verfahren nach Anspruch 1, wobei der Schritt des Erzeugens in einer Argonatmosphäre bei 1149-1260 °C für 15-60 Minuten erfolgt.

17. Verfahren nach Anspruch 1 oder 16, wobei der Schritt des Schmelzens in einer Argonatmosphäre bei 1316-1427 °C für 15-60 Minuten erfolgt.

18. Verfahren nach Anspruch 1, 16 oder 17, wobei der Schritt des Entgasens das Vakuumheißentgasen des Pulvers bei 343-399 °C für 4-15 Stunden umfasst.

19. Verfahren nach einem der Ansprüche 1 oder 16 bis 18, wobei der Schritt des Warmumformens bei 343-399 °C für 5-30 Minuten erfolgt.

Revendications

1. Procédé de production d'un alliage d'aluminium comprenant : la fourniture d'un alliage d'aluminium comprenant :

(a) de 0,6 à 2,9 % en poids de scandium ;
(b) de 1,5 à 25 % en poids de nickel ;
(c) de 0,4 à 20 % en poids de gadolinium ;
(d) de 0,4 à 2,9 % en poids de zirconium ; et
(e) le reste étant de l'aluminium ;

le procédé comprenant les étapes de : production de l'alliage par une technique de solidification rapide utilisant une vitesse de refroidissement d'au moins 10^3 °C/seconde ou plus, dans lequel la technique de solidification rapide comprend au moins les étapes suivantes :

la création d'un lingot ayant une composition prédéterminée ;
la fusion du lingot ;
l'atomisation du lingot fondu pour former une poudre ;
le dégazage de la poudre ;
le compactage de la poudre pour créer une billette ;
le travail à chaud de la billette en une forme prédéterminée ;
dans lequel l'étape de compactage comprend la compression à chaud sous vide de la poudre à 343 à 399 °C pendant 1 à 5 heures.

2. Procédé selon la revendication 1, dans lequel l'alliage comprend une matrice de solution solide d'aluminium et une dispersion d'Al_3Ni et d'Al_3X, l'Al_3X ayant une structure $L1_2$ dans laquelle X comprend du scandium et au moins l'un du gadolinium et du zirconium.

3. Procédé selon la revendication 1 ou 2, dans lequel l'alliage est dépourvu de magnésium.

4. Procédé selon l'une quelconque des revendications précédentes, dans lequel l'alliage peut être utilisé à des températures de -420 °F (-251 °C) à 650 °F (343 °C).

5. Procédé de fabrication d'un composant d'avion, d'un composant de fusée, et d'un composant d'automobile ; le procédé comprenant l'utilisation de l'alliage fabriqué par le procédé selon l'une quelconque des revendications précédentes.

6. Procédé selon la revendication 5, dans lequel le composant de fusée comprend au moins l'un d'une gaine structurale, d'un carter de turbopompe, d'un rotor de turbine, d'un carter de rotor de turbine, d'un impulseur, d'une vanne, d'un carter de vanne, d'un injecteur, d'une buse, d'un support, d'une conduite, d'un composant de plomberie, et d'un composant structural de fusée.

7. Procédé selon la revendication 5, dans lequel le composant d'avion comprend au moins l'un d'un carter d'entrée d'air, d'un ensemble stator, d'une boîte de vitesses, d'un carter de roulement, d'un carter de joint carbone, d'un dôme, d'un couvercle, d'une aube, et d'un stator.

8. Procédé selon l'une quelconque des revendications précédentes, dans lequel l'alliage est constitué de :

(a) 1 à 2,9 % en poids de scandium ;
(b) 6 à 10 % en poids de nickel ;
(c) 2 à 10 % en poids de gadolinium,
(d) 0,5 à 2,9 % en poids de zirconium,
(e) le reste étant de l'aluminium plus des impuretés inévitables.

9. Procédé selon la revendication 8, dans lequel l'alliage est constitué de :

(a) 2,15 % en poids de scandium ;
(b) 8,4 % en poids de nickel ;
(c) 4,1 à 8,8 % en poids de gadolinium,
(d) 1,5 à 2,5 % en poids de zirconium,
(e) le reste étant de l'aluminium plus des impuretés inévitables.

10. Procédé selon l'une quelconque des revendications 1 à 7, dans lequel l'alliage est constitué de l'une des compositions suivantes, en pourcentage en poids :

Al-(6-10)Ni-(1-2,9)Sc-(6-10)Gd-(0,5-2,9)Zr ; et
Al-8,4Ni-2,15Sc-8,8Gd-1,5Zr.

11. Procédé selon la revendication 10, dans lequel l'alliage est constitué de la composition suivante, en pourcentage en poids : Al-8,4Ni-2,15Sc-8,8Gd-2,5Zr.

12. Alliage d'aluminium selon la revendication 11, dans lequel l'alliage comprend une matrice de solution solide d'aluminium, une pluralité de dispersoïdes d'Al_3(Sc,Gd,Zr) de ayant une structure $L1_2$, et une pluralité de dispersoïdes d'Al_3Ni.

13. Procédé selon la revendication 11, dans lequel l'alliage comprend en outre jusqu'à 50 % en volume d'une seconde phase de renforcement.

14. Procédé selon la revendication 13, dans lequel la seconde phase de renforcement comprend au moins l'un de : un oxyde, un carbure, un nitrure, un oxynitrure, un oxycarbonitrure, un siliciure, un borure, un alliage ferreux, du bore, du graphite, du tungstène, du titane, du SiC, du Si_3N_4, de l'Al_2O_3, du B_4C, du Y_2O_3, du $MgAl_2O_4$, du TiC et du TiB_2.

15. Procédé selon la revendication 1, dans lequel la technique de solidification rapide comprend au moins l'un des : filage par fusion, trempe brusque, atomisation, dépôt par pulvérisation, pulvérisation de plasma sous vide, pulvérisation à froid, fusion laser, alliage mécanique, cryobroyage, tournage centrifuge, et broyage à boulets.

16. Procédé selon la revendication 1, dans lequel l'étape de création est réalisée sous atmosphère d'argon à 1149 à 1260 °C pendant 15 à 60 minutes.

17. Procédé selon la revendication 1 ou 16, dans lequel l'étape de fusion est réalisée sous atmosphère d'argon à 1316 à 1 427 °C pendant 15 à 60 minutes.

18. Procédé selon la revendication 1, 16 ou 17, dans lequel l'étape de dégazage comprend la compression à chaud sous vide de la poudre à 343 à 399 °C pendant 4 à 15 heures.

19. Procédé selon l'une quelconque des revendications 1 ou 16 à 18, dans lequel l'étape de travail à chaud survient à 343 à 399 °C pendant 5 à 30 minutes.

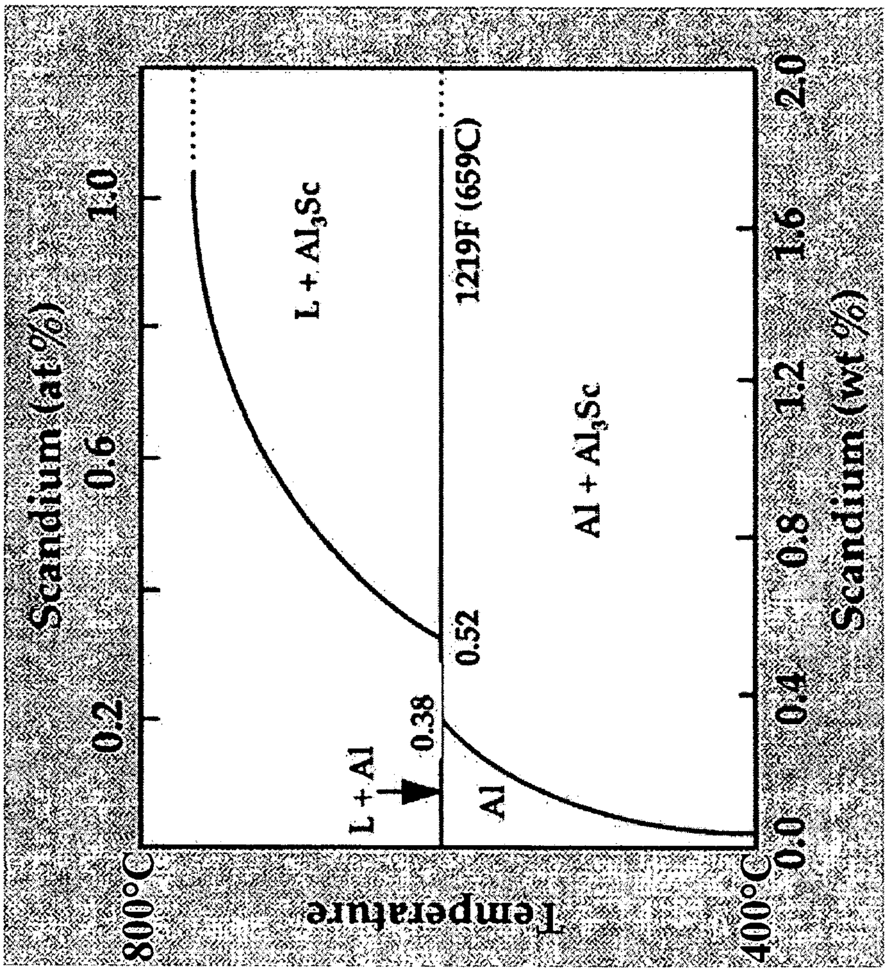
Scandium (at %)
0.2
0.6
1.0
800°C
Temperature
400°C
0.0
0.4
0.8
1.2
1.6
2.0
Scandium (wt %)
L + Al
0.38
Al
0.52
L + Al₃Sc
1219F (659C)
Al + Al₃Sc

FIGURE 1

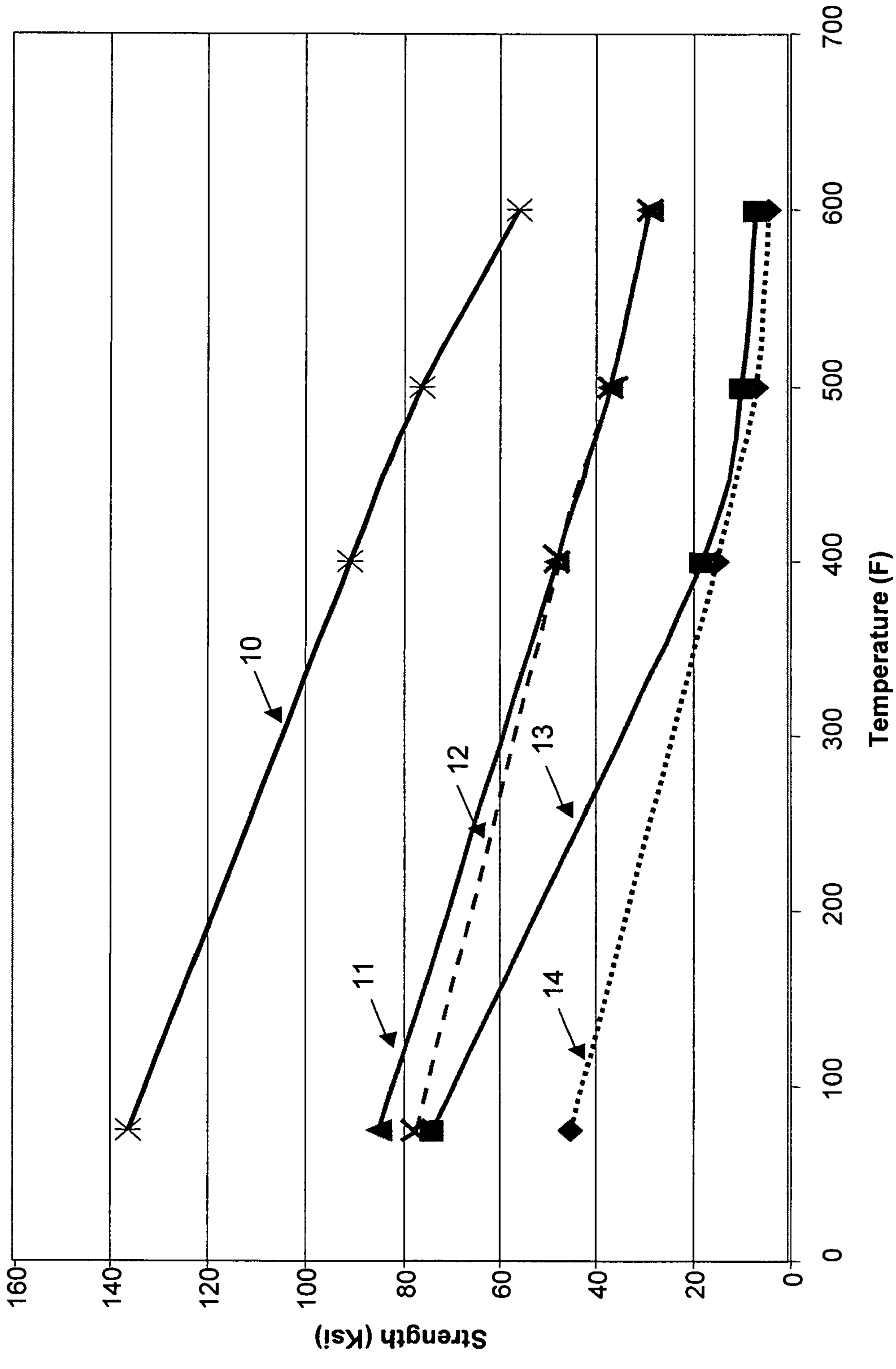
Strength (Ksi)
160
140
120
100
80
60
40
20
0
Temperature (F)
0
100
200
300
400
500
600
700
10
11
12
13
14

FIGURE 2

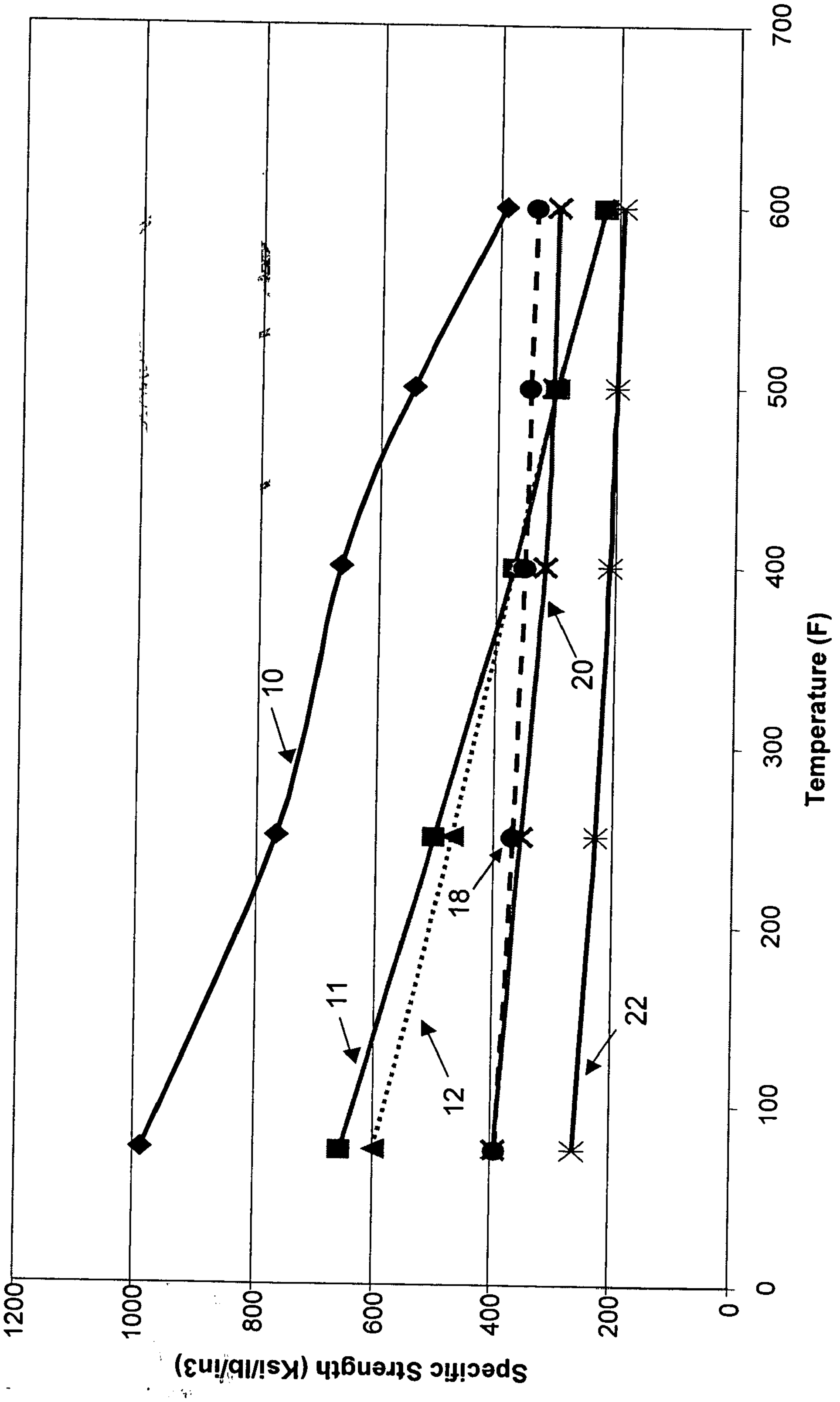
Specific Strength (Ksi/lb/in3)
1200
1000
800
600
400
200
0
Temperature (F)
0
100
200
300
400
500
600
700
10
11
12
18
20
22

FIGURE 3

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

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- RU C12001144 **[0008]**