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(54) Title of the Invention: **Aluminium alloy for casting**
Abstract Title: **An aluminium-silicon-nickel casting alloy**

(57) An aluminium alloy having high Young's modulus which comprises (by weight): 8.5-12.5 % silicon, 2.5-9.0 % nickel, 0.001-0.05 % of nucleant selected from one or more of TiB, TiB_2, AlB_2, B, NbB, NbB_2, TiC and BC; two or more of: ≤3.5 % copper, 0.1-0.8 % magnesium, ≤1.0 % manganese, ≤1.5 % zinc, ≤1.0 % beryllium, ≤1.0 % lithium, ≤0.2 % titanium, ≤0.2 % vanadium, ≤0.2 % silver, ≤0.2 % niobium, ≤0.4 % iron, ≤0.5 % chromium and/or ≤0.2 % zirconium; optionally 10-3000 ppm of at least one eutectic modifying element selected from one or more of Sr, Na, Sb, Y, Yb and Eu; with the balance being aluminium and impurities. The alloy can be made into a cast product which is solution heat treated, quenched and then aged at a temperature in the range 180-230 ^{0}C for 1-100 hours. The alloy can be used to make vehicle components.

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

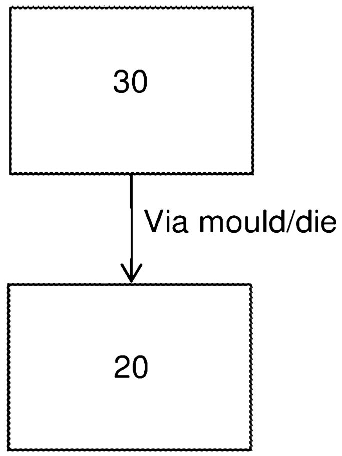

FIG. 1

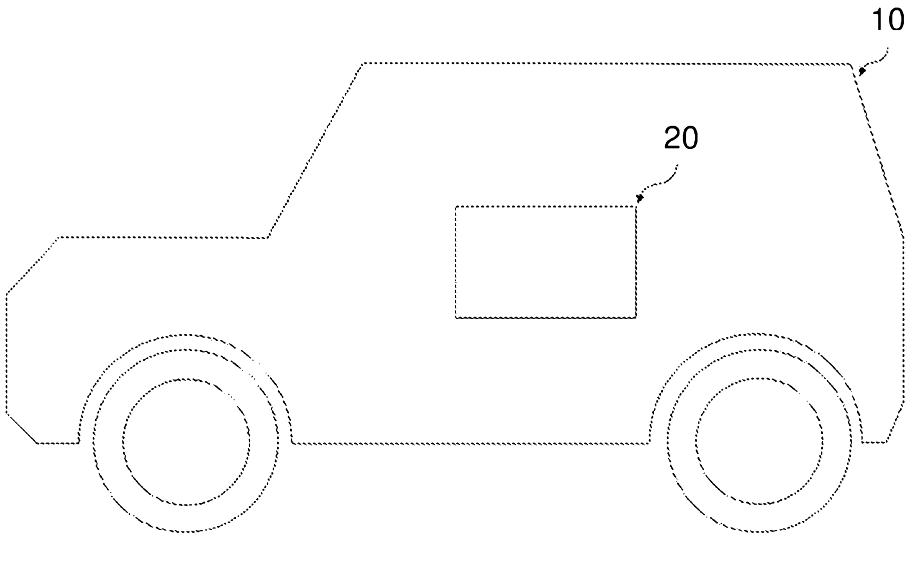

FIG. 2

ALUMINIUM ALLOY FOR CASTING

TECHNICAL FIELD

The present disclosure relates to an alloy and particularly, but not exclusively, to aluminium alloys for use in castings of structural components. Aspects of the invention relate to an alloy composition, the use of such an alloy composition, a cast product comprising an alloy composition, a vehicle comprising a cast product, and to a method of forming a cast product.

BACKGROUND

In the automotive industry, the use of aluminium alloys has been steadily increasing, gradually replacing components that were traditionally formed of steel. Compared with steel, aluminium has become a material of choice due to its strength and environmental credentials. Reduction in vehicle weight through use of aluminium alloys allows for improved fuel efficiency during the vehicle's lifetime, and 90% or more of the aluminium may be recycled when the vehicle is scrapped at the end of its life or when component parts are replaced. Accordingly, development of alloy compositions and heat treatment processes continues in order to provide desired or improved properties for fulfilling the particular requirements of specific components.

The process of casting aluminium alloys is commonly used for the production of a wide variety of shaped components. In the automotive industry, as well as in other industries such as aerospace, construction and general engineering, it is particularly desirable to produce cast aluminium parts that have improved Young's modulus in combination with low density and high strength.

Young's modulus (E) is a measure of the stiffness or rigidity of a solid material or component, sometimes also referred to as the resistance to deflection. It therefore provides a measure of the ability of a material to withstand changes in length when under lengthwise tension or compression. Generally, the higher the Young's modulus value, the stiffer is the material. Young's modulus is therefore a critical consideration for determining usefulness of structural components, in particular shaped castings. Pure aluminium has a Young's modulus in the region of ~70 GPa. Currently, there are few options for increasing Young's modulus in aluminium alloys and aluminium-based materials used to make shaped castings.

In the manufacture of materials with a high Young's modulus, the use of ceramic particles uniformly distributed within an aluminium matrix has been a key strategy. Methods for introducing ceramic particles are generally based on powder metallurgy, which due to the use of finely divided metal powder requires strict safety precautions to avoid biological exposure and risk of explosion. Further, the chemical composition of the matrix/particle interface, and hence their cohesion, can be difficult to control in view of the risk of surface contamination of the metal and/or ceramic powder before sintering or when the ceramic particles are added in large quantities. Moreover, when high volume fraction of ceramic particles is used, the elongation properties of the resulting composite material typically decline. Aluminium/ceramic composites manufactured by powder metallurgy route are generally suitable only for production on a small scale which, combined with associated high manufacturing costs, makes such materials unattractive for high volume components, such as those required in the motor industry.

It is widely known that the physical and mechanical properties of alloys are determined not only by their chemical composition, but also by the microstructure of the composition. Thus the influence of alloying elements on the Young's modulus depends on their state. For example, if the alloying elements are in a solid solution phase, the magnitude of the Young's modulus is largely determined by the nature of atomic interactions. If the alloying elements form second phases, the magnitude of the Young's modulus is determined by the volume fraction and the intrinsic modulus of the second phase. In relation to aluminium alloys, the second phase is more effective for stiffness improvement than the solid solution.

Examples of cast aluminium alloys having a Young's modulus in excess of that of pure aluminium are documented in the prior art.

EP-A-0340788 describes a mechanically alloyed aluminium-base alloy having a modulus of elasticity at room temperature of at least 90 GPa and containing 10-25 wt.% titanium, which may be partly or wholly replaced by vanadium or zirconium, niobium, tantalum, yttrium, tungsten, cerium, erbium, chromium, iron, cobalt, nickel and copper.

EP-A-0391815 describes an aluminium-based alloy of the 7000 series having a high modulus of at least 74 GPa, high mechanical strength, good tenacity and good corrosion resistance. The alloy comprises 5.5-8.45 wt.% Zn, 2-3.5 wt.% Mg, 0.5-2.5 wt.% Cu, ≤0.5 wt.% Fe, ≤0.5 wt.% Si, other elements ≤0.05 wt.% each and ≤0.15% in total with 0.1≤Zr≤0.5 wt.%, 0.3≤Cr≤0.6 wt.%, 0.3≤Mn≤1.1 wt. %.

US-A-5667600 describes an investment cast aluminium-based alloy having a high modulus containing 1 to 99 wt.% beryllium.

US-A-5716467 describes an aluminium-based alloy containing 1-99 wt.% beryllium, and methods for its production using semi-solid processing.

It has been found that beryllium, along with lithium, has a tendency to increase the brittleness of aluminium alloys and, if present in substantial amounts, therefore contributes to difficulty in making shaped castings with complex geometry, as well as being costly and toxic to handle due to their reactivity.

Therefore, while the prior art indicates that aluminium alloys having a Young's modulus exceeding that of pure aluminium combined with other beneficial mechanical properties are known, it has hitherto proved challenging to produce such alloys in the form of shaped components in high volumes yet at acceptable cost.

Thus there remains a need to provide an aluminium alloy for producing shaped components, including those of complex geometry, which alloy has a high Young's modulus combined with high strength under as-cast condition to facilitate use of thinner gauge parts yet still retain the necessary stiffness and strength for their intended use.

Accordingly, it is an aim of the present invention to provide a cast aluminium alloy composition for shaped components, the cast alloy having an enhanced Young's modulus, as well as excellent yield strength, ultimate tensile strength and elongation under heat treated condition.

These and other uses, features and advantages of the invention should be apparent to those skilled in the art from the teachings provided herein.

SUMMARY OF THE INVENTION

Against this background, the invention resides in a first aspect in an aluminium alloy for manufacturing shaped castings comprising:

6.5 to 17.5 wt.% silicon; and

0.5 to 11.0 wt.% nickel.

Whilst not being bound by theory, it is believed that the use of silicon as the primary alloying element in the aluminium alloy of the present invention effectively decreases the liquid line to ensure good castability, as well as forming an Al-Si eutectic microstructure which improves the strength and the Young's modulus of the alloy. The use of nickel as the secondary alloying element provides further improvement of the Young's modulus.

The aluminium alloy of the invention enables the production of castings having significantly improved Young's modulus, whilst at the same time maintaining or improving upon yield strength and ultimate tensile strength. Further, and contrary to expectation, reasonable ductility can be achieved despite the improved Young's modulus.

In embodiments, the aluminium alloy may comprise at least two further elements selected from the following:

copper in an amount of 5.5 wt.% or less;
magnesium in an amount of 2.0 wt.% or less;
manganese in an amount of 1.0 wt.% or less;
zinc in an amount of 2.0 wt.% or less;
beryllium in an amount of 2.0 wt.% or less;
lithium in an amount of 2.0 wt.% or less;
titanium in an amount of 0.3 wt.% or less;
vanadium in an amount of 0.3 wt.% or less;
silver in an amount of 0.3 wt.% or less;
niobium in an amount of 0.3 wt.% or less;
iron in an amount of 0.8 wt.% or less;
chromium in an amount of 1.0 wt.% or less; and
zirconium in an amount of 0.3 wt.% or less.

In some embodiments, the aluminium alloy may have a composition of:

8.5-12.5 wt.% silicon as primary alloying element;

2.5-9.0 wt.% nickel as secondary alloying element;

at least two elements from the group of:

<3.5 wt.% copper, 0.1-0.8 wt.% magnesium, <1.0 wt.% manganese, <1.5 wt.% zinc, <1.0 wt.% beryllium, <1.0 wt.% lithium, <0.2 wt.% titanium, <0.2 wt.% vanadium, <0.2 wt.% silver, <0.2 wt.% niobium, <0.4 wt.% iron, <0.5 wt.% chromium, <0.2 wt.% zirconium; and

0.001 to 0.05 wt.% of a nucleant selected from one or more of the group consisting of TiB, TiB2, AlB2, B, NbB, NbB2, TiC, and BC, with the balance being aluminium and inevitable impurities.

In some embodiments, the aluminium alloy may comprise a composition of:

8.5-12.5 wt.% silicon;

2.5-9.0 wt.% nickel; and

at least two elements from the group of 0.3-3.5 wt.% copper, 0.1-0.8 wt.% magnesium, <0.6 wt.% manganese, <1.5 wt.% zinc, <1.0 wt.% beryllium, <1.0 wt.% lithium, <0.2 wt.% titanium, <0.2 wt.% vanadium, <0.2 wt.% silver, <0.2 wt.% niobium, <0.4 wt.% iron, <0.5 wt.% chromium, <0.2 wt.% zirconium, with the balance being aluminium and inevitable impurities.

In some embodiments, the aluminium alloy may comprise a composition of:

9.0-12.0 wt.% silicon;

3.5-7.0 wt.% nickel; and

at least two elements from the group of 0.5-3.0 wt.% copper, 0.15-0.5 wt.% magnesium, <0.5 wt.% manganese, <1.0 wt.% zinc, <0.5 wt.% beryllium, <0.5 wt.% lithium, <0.15 wt.% titanium, <0.1 wt.% vanadium, <0.1 wt.% silver, <0.1 wt.% niobium, <0.2 wt.% iron, <0.3 wt.% chromium, <0.15 wt.% zirconium, with the balance being aluminium and inevitable impurities.

In embodiments, the aluminium alloy of the invention may further comprise from 10 to 3,000 ppm of at least one eutectic modifying agent selected from the group consisting of: strontium, sodium, antimony, yttrium, ytterbium and europeum.

In embodiments, the aluminium alloy of the invention may further comprise from 0.001 to 0.05 wt.% of a nucleant selected from one or more of the group consisting of: TiB, TiB_2, AlB_2, B, NbB, NbB_2, TiC, and BC.

An example of a casting alloy according to one embodiment of the invention has the following composition: 6.5-17.5 wt.% Si and 0.5-11.0 wt.% Ni and at least two elements from the group of <5.5 wt.% Cu, <2 wt.% Mg, <1.0 wt.% Mn, <2.0 wt.% Zn, <2.0 wt.% Be, <2.0 wt.% Li, <0.3 wt.% Ti, <0.3 wt.% V, <0.3 wt.% Ag, <0.3 wt.% Nb, <0.8 wt.% Fe, <1.0 wt.% Cr, <0.3 wt.% Zr, 10-3,000 ppm of an element selected from Sr, Na, Sb, Y, Yb, and Eu and 0.001 to 0.05 wt.% of at least one of TiB, TiB_2, AlB_2, B, NbB, NbB_2, TiC, and BC, balanced by aluminium and inevitable impurities.

In embodiments, a cast aluminium alloy having a Young's modulus of at least about 80 GPa may be achieved. Moreover, such improved modulus may be achieved alongside advantageous yield strength and tensile strength properties, for example, a yield strength of at least about 180 MPa and an ultimate tensile strength of at least about 250 MPa may be achieved. The aluminium alloy of the invention may also have elongation properties that are acceptable, such as an elongation of at least 0.5%. Such properties are beneficial when the cast alloy is used for vehicle components or the like.

Thus, according to another aspect of the invention presented herein, there is provided a cast product comprising the aluminium alloy composition as hereinbefore described, wherein the cast product has a Young's modulus of at least about 80 GPa, or from about 80 GPa to about 95 GPa, or from about 85 GPa to about 90 GPa.

In an embodiment, the cast product has a Young's modulus of at least 80 GPa, or from about 80 GPa to about 95 GPa, or from about 85 GPa to about 90 GPa, a yield strength of at least about 180 MPa, or from about 180 MPa to about 250 MPa, or from about 200 MPa to about 240 MPa, and an ultimate tensile strength of at least about 250 MPa, or from about 250 MPa to about 300 MPa, or from about 260 MPa to about 290 MPa.

In another embodiment, the cast product has an elongation of at least 0.5%, or at least about 2.5%, or from about 2.5% to about 5%.

According to another aspect, there is provided the use of the aforementioned aluminium alloy in the manufacture of a cast product.

According to another aspect, there is provided a cast product comprising the aforementioned aluminium alloy, wherein the cast product may be a vehicle component, optionally selected from one or more of the group consisting of: an engine component; a vehicle wheel; a steering wheel; a steering column; a frame member; a gear box; a powertrain component; a chassis component; a body component and a transmission system.

According to a further aspect, there is provided a vehicle comprising the cast product as described above.

According to a further embodiment the vehicle may be selected from the group consisting of: an automobile; a motorcycle; a locomotive; a watercraft and an aircraft.

According to a further aspect, there is provided a process for manufacturing a cast product, the process comprising casting an aluminium alloy having a composition as hereinbefore described into a mould or die that defines the cast product.

According to a further embodiment, there is provided the process as described above, wherein the cast product may be manufactured by die casting.

In embodiments, the cast product is a heat treated product and/or the process for manufacturing the cast product includes heat treating the alloy composition. For example, the cast product may be processed by heat treatment after casting for enhancement of the mechanical properties.

In embodiments, the cast product may be heat treated by solutionising the alloy at elevated temperature for a first period of time, followed by quenching with a quenching medium, such water, and aging the alloy at a temperature lower than the solutionising elevated temperature but above ambient temperature for a further period of time.

In embodiments, the cast product may be solutionised at 490-540 ºC for about 1-24 hours. In other embodiments, the cast product may be aged at 150-230 ºC for about 1-100 hours. For example, the cast product may be aged at 180-230 ºC for about 1-100 hours.

According to a further aspect, there is provided a method of forming a cast aluminium alloy product, comprising the steps of:

(a) forming an aluminium melt comprising 6.5 to 17.5 wt.% silicon and 0.5 to 11.0 wt.% nickel;
(b) introducing the melt into a mould and solidifying the melt to form an as-cast alloy; and
(c) heat treating the as-cast alloy to form the cast aluminium alloy product.

In one embodiment, there is provided a method of forming a cast aluminium alloy product, comprising the steps of:

(a) forming an aluminium melt from 6.5 to 17.5 wt.% silicon and 0.5 to 11.0 wt.% nickel, and at least two elements from the group of: copper in an amount of 5.5 wt.% or less; magnesium in an amount of 2.0 wt.% or less; manganese in an amount of 1.0 wt.% or less; zinc in an amount of 2.0 wt.% or less; beryllium in an amount of 2.0 wt.% or less; lithium in an amount of 2.0 wt.% or less; titanium in an amount of 0.3 wt.% or less; vanadium in an amount of 0.3 wt.% or less; silver in an amount of 0.3 wt.% or less; niobium in an amount of 0.3 wt.% or less; iron in an amount of 0.8 wt.% or less; chromium in an amount of 1.0 wt.% or less; and zirconium in an amount of 0.3 wt.% or less; with the balance being aluminium and inevitable impurities;
(b) adding to the melt 10-3000 ppm, or 50-300 ppm, or 100-200 ppm, of at least one eutectic modifying element selected from the group consisting of Sr, Na, Sb, Y, Yb, and Eu;
(c) adding to the melt 0.001 to 0.05 wt.% of at least one nucleant selected from the group consisting of TiB, TiB_2, B, NbB, NbB_2, TiC, and BC;
(d) introducing the melt into a mould and solidifying the melt to form an as-cast alloy; and
(e) heat treating the as-cast alloy to form the cast aluminium alloy product.

Within the scope of this application it is expressly intended that the various aspects, embodiments, examples and alternatives set out in the preceding paragraphs, in the claims and/or in the following description and drawings, and in particular the individual features thereof, may be taken independently or in any combination. That is, all embodiments and/or features of any embodiment can be combined in any way and/or combination, unless such features are incompatible. The applicant reserves the right to change any originally filed claim or file any new claim accordingly, including the right to amend any originally filed claim to depend from and/or incorporate any feature of any other claim although not originally claimed in that manner.

BRIEF DESCRIPTION OF THE DRAWINGS

One or more embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a flow chart showing the cast product manufacturing process.

Figure 2 is a drawing of a vehicle comprising a cast product.

DETAILED DESCRIPTION

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs.

A number of definitions are provided below that will assist in the understanding of the invention.

As used herein, the term "comprising" or “containing” means any of the recited elements are necessarily included, and where indicated other elements may optionally be included as well. "Consisting essentially of” means any recited elements are necessarily included, elements that would materially affect the basic and novel characteristics of the listed elements are excluded, and other elements may optionally be included. "Consisting of” means that all elements other than those listed are excluded. Embodiments defined by each of these terms are within the scope of this invention.

The term “alloy” is used herein to denote a metallic composition comprising a mixture of a predominating metallic element and other elements, including impurities.

The term “casting” as used herein embraces a variety of casting processes for producing products, such as bars, plates or sheets, which may be suitable for further processing, such as by rolling, extrusion, flow forming or forging, and for producing shaped components directly using moulds, for example, by gravity casting or vacuum casting.

In a gravity casting process the mould may take the form of a reusable die. The casting process involves a furnace, metal and the mould. The alloy comprising aluminium is first melted in the furnace and then poured or injected into the mould. The mould is filled under gravity rather than by use of high pressure. After solidification of the alloy and release from the mould, the resulting casting may be subjected to additional tooling or trimmed and finished. The cutting of the cast metal product is also known as machining. Casting processes can produce large and small component parts, with geometrically complex shapes.

Once cast, the alloy may be subjected to heat treatment, typically involving solutionising (sometimes referred to as “solution heat treatment”) followed by aging (sometimes referred to as “artificial aging”). The resulting heat treated cast parts are typically of high strength and can be subjected to considerable loads when in use.

As mentioned, components manufactured via die casting processes of the present invention are also referred to as ‘parts’ and broadly refer to any metal object manufactured via the casting process. The parts are often comprised of geometrically complex shapes that perform a defined function. Components manufactured according to the present invention are particularly suitable for use in motor vehicles, locomotives, static engines, watercraft (marine) and aircraft.

As used herein, the term “balance”, when used in reference to a particular element, is used to describe that the remainder of the composition (in wt.%), excluding any alloying additions, is comprised of the designated element. Hence, the total composition including the “balance” element in combination with other stated alloying elements is equal to 100 wt.% of the alloy composition. The term “impurity” refers to a metallic or non-metallic element that is present in an alloy but which is not added intentionally. In embodiments of the present invention where only specific component elements are specified, the balance of the alloy may comprise aluminium.

The term “mould”, as used herein, is referring to a hollow container used to give shape to molten or hot liquid material when it cools and hardens.

The term “die”, as used herein, is referring to a block with a special shape or with a pattern cut into it that is used for shaping pieces of metal.

The phrase “cast product” is used herein to denote an entity that has been cast in metal from a die or a mould.

The term “as-cast” is used herein to refer to a casting in the condition in which it comes out of the foundry, before any work-hardening or additional heat treatment is carried out.

As used herein, the term “vehicle” is used to denote any means in or by which people, animals or goods may be transported or conveyed. Typically, vehicles may include road transport motor vehicles as well as rail locomotives. Watercraft may include marine vessels, such as boats, ships, submarines and hovercraft. Aircraft may include fixed wing or non-fixed wing aircraft, as well as spacecraft.

As mentioned the casting processes can produce large and small cast products also referred to as component parts. The term “vehicle component” is referring to any part that is for deployment in a vehicle.

As a primary alloying element in the composition of the present invention, silicon may effectively decrease the liquid line to provide good castability. In particular, the silicon addition may form an Al-Si eutectic microstructure, improving the strength of the alloy. Accordingly, in embodiments, the silicon content of the alloy may be at least about 6.5 wt.%, or at least about 7.5 wt.%, or at least about 9.0 wt.%. On the other hand, in improving the strength of the alloy, elongation (or ductility) may be sacrificed. Accordingly, to maintain elongation within acceptable parameters, the silicon content may be limited to about 17.5 wt.% or less, or about 12.5 wt.% or less, or about 12.0 wt.% or less.

Nickel is also a primary alloying element in the composition of the present invention and contributes to the enhancement of the Young’s modulus. The microstructure of the hypoeutectic Al-Ni binary alloys consists of the ε-(Al_3Ni) phase in the aluminium matrix. It is found that the Young’s modulus of the aluminium alloy may be significantly improved against the volume fraction of the ε-phase. Accordingly, in embodiments, the nickel content of the alloy may be at least about 0.5 wt.%, or at least about 2.5 wt.%, or at least about 3.5 wt.%. Up to the Al-Ni eutectic composition, the primary ε-phase in the alloy results in a noticeable increase in the Young's modulus values. Accordingly, in embodiments, the nickel content may be limited to about 11.0 wt.%, or about 9.0 wt.%, or about 7.0 wt.% or less, or to less than the eutectic content which is about 5.7 wt.% or less.

Copper and magnesium may serve as strengthening elements in the alloy composition according to the present invention and the inclusion of one or both these elements may be beneficial. Thus, in embodiments, when copper is included, it may be present in an amount of at least about 0.3 wt.%, or at least about 0.5 wt.%, and when magnesium is included, it may be present in an amount of at least about 0.1 wt.%, or at least about 0.15 wt.%. On the other hand, copper may also reduce resistance to general corrosion and hot tear, and magnesium may be evaporated through oxidation during melting of the alloy. Thus, in embodiments, the copper content may be limited to about 5.5 wt.% or less, or about 3.5 wt.% or less, or about 3.0 wt.% or less, and the magnesium content may be limited to about 2.0 wt.% or less, or about 0.8 wt.% or less, or about 0.5 wt.% or less.

The inclusion of one or more elements selected from beryllium, lithium, manganese and zirconium may also serve to increase the Young's modulus of the alloy according to the present invention. However, these elements may potentially cause difficulties in melting and be detrimental to castability and ductility. Therefore, in embodiments, the amounts of each of these elements in the alloy composition of the invention may be limited such that the amount of beryllium may be less than about 2.0 wt.%, or less than about 1.0 wt.%, or less than about 0.5 wt.%; the amount of lithium may be less than about 2.0 wt.%, or less than about 1.0 wt.%, or less than about 0.5 wt.%; the amount of manganese may be less than about 1.0 wt.%, or less than about 0.6 wt.%, or less than about 0.4 wt.%; the amount of zirconium may be less than about 0.3 wt.%, or less than about 0.2 wt.%, or less than about 0.15 wt.%.

Iron may be present in the alloy of the invention at low levels to avoid or reduce formation of undesirable large compounds that may have a detrimental effect on the mechanical properties of the alloy. Thus, according to other embodiments, the iron content of the alloy composition may be less than about 0.8 wt.%, or less than about 0.4 wt.%, or less than about 0.2 wt.%.

Manganese may be especially beneficial for neutralising the effect of any iron in the composition, for example, by combining with iron to alter the morphology of Fe-containing compounds from needle-like morphology to a nodular morphology. Additionally, the presence of manganese may serve to reduce the tendency of a die to stick to die cast parts. Thus, according to a further embodiment, the manganese (Mn) content of the alloy may be less than 1.0 wt.%, or less than 0.6 wt.%, or less than 0.4 wt.%.

The inclusion of titanium in the alloy of the invention at low levels may be advantageous, for example, to restrict the growth of primary dendrites. Thus according to a further embodiment, the titanium (Ti) content of the alloy may be less than about 0.3 wt.%, or less than about 0.2 wt.%, or less than about 0.15 wt.%.

Modification to change the morphology of the eutectic microstructure of the alloy composition may be achieved by addition of one or more eutectic modifying agents. For example, the morphology of silicon rich crystals in the eutectic mixture may be modified by addition of small amounts of elements such as sodium, strontium or antimony to the melt to alter the eutectic structure and to yield silicon rich crystals having a fine structure. In this way, further improvements to the mechanical properties of the cast parts produced from the alloy according to the invention may be achieved, for example, to allow reduction in the component weight by casting with thinner walls. Accordingly, in embodiments, the alloy composition of the invention may further comprise from 10 to 3,000 ppm, or from 50 to 500 ppm, or from 100 to 200 ppm, of at least one eutectic modifying agent selected from the group consisting of: strontium, sodium, antimony, yttrium, ytterbium and europeum. Addition of strontium as a eutectic modifying agent is especially useful.

Further modifications to the microstructure of the alloy composition may be achieved through inclusion of a nucleation agent (nucleant), especially when the addition thereof occurs after melting of the aluminium and alloying metals and prior to casting. For example, inclusion of a nucleant may result in grain refinement such that upon solidification of the alloy on casting, the alloy achieves a refined microstructure with small equiax aluminium crystals. The alloy composition may include at least one nucleant in an amount of from 0.001 to 0.05 wt.%.

In embodiments, the alloy composition may include at least one nucleant selected from the group consisting of: TiB, TiB_2, AlB_2, B, NbB, NbB_2, TiC, and BC. Such compounds may be added *per* se or via other compositions, such as through addition of an Al-5Ti-1B master alloy.

In another aspect of the invention, there is provided a method of forming a cast aluminium alloy product, comprising the steps of:

(a) forming an aluminium melt comprising 6.5 to 17.5 wt.% silicon and 0.5 to 11.0 wt.% nickel;

(b) introducing the melt into a mould and solidifying the melt to form an as-cast alloy; and

(c) heat treating the as-cast alloy to form the cast aluminium alloy product.

In one embodiment, there is provided a method of forming a cast aluminium alloy product, comprising the steps of:

(a) forming an aluminium melt from 6.5 to 17.5 wt.% silicon and 0.5 to 11.0 wt.% nickel, and at least two elements from the group of: copper in an amount of 5.5 wt.% or less; magnesium in an amount of 2.0 wt.% or less; manganese in an amount of 1.0 wt.% or less; zinc in an amount of 2.0 wt.% or less; beryllium in an amount of 2.0 wt.% or less; lithium in an amount of 2.0 wt.% or less; titanium in an amount of 0.3 wt.% or less; vanadium in an amount of 0.3 wt.% or less; silver in an amount of 0.3 wt.% or less; niobium in an amount of 0.3 wt.% or less; iron in an amount of 0.8 wt.% or less; chromium in an amount of 1.0 wt.% or less; and zirconium in an amount of 0.3 wt.% or less; with the balance being aluminium and inevitable impurities;

(b) adding to the melt 10-3000 ppm, or 50-300 ppm, or 100-200 ppm, of at least one eutectic modifying element selected from the group consisting of Sr, Na, Sb, Y, Yb, and Eu;

(c) adding to the melt from 0.001 to 0.05 wt.% of at least one nucleant selected from the group consisting of TiB, TiB_2, B, NbB, NbB_2, TiC, and BC;

(d) introducing the melt into a mould and solidifying the melt to form an as-cast alloy; and

(e) heat treating the as-cast alloy to form the cast aluminium alloy product.

In embodiments, the aluminium melt may be homogenised prior to addition of the eutectic modifying element. After addition of the eutectic modifying element, the molten alloy may be degassed, for example using argon, prior to addition of the nucleant(s).

The cast aluminium alloy product thus formed may be in the form of a vehicle component 20, for example, to be deployed in an automobile 10 as shown in Figure 2, or in a motorcycle, a locomotive, a watercraft or an aircraft. The cast component itself may be an engine component; a vehicle wheel; a steering wheel; a steering column; a frame member; a gear box, a powertrain component, a chassis component, a body component and transmission system. It will be appreciated that the aforementioned list of vehicles and the aforementioned list of components are not intended to be exhaustive, and other vehicles and/or components are contemplated.

The invention is further illustrated by the following non-limiting examples.

<u>Example 1</u>

A series of alloys were prepared by gravity casting which is a typical liquid metallurgy route. The alloys were manufactured using Al-7.1Si-0.3Mg (marked as alloy No. 1) as the base material. Ingots were melted in a clay-graphite crucible using an electric resistance furnace. Alloying elements were added to the molten metal to obtain the required compositions, during which Mg, Si, Ni, Cu and Mn were added in the form of master alloys. The furnace temperature was controlled at 750 ℃, and a melt of 10 kg was prepared each time. After one hour of homogenisation, Al-10 wt.% Sr master alloy was added into the melt to provide Sr as the eutectic modifying element to the required content. The molten metal was then degassed using pure argon injected into the melt by means of a rotary degassing impeller at a speed of 350 rpm for 4 min. After degassing, the top surface of the melt was covered by commercial granular flux, and then the melt was held for 15 mins for temperature recovery. Al-5Ti-1B master alloy was subsequently added into the melt to provide a nucleant in the form of TiB_2 as grain refiner. The melt was poured at 730 ℃ into a preheated permanent mould designed according to ASTM B-108. Compositions, in weight percent, of the conventional cast Al alloy (alloy No. 1) as well as some high modulus aluminium alloys (alloys No. 2-18) of the present invention are listed in Table 1.

Table 1. Chemical composition in wt.%.

Alloy No.	Si	Ni	Cu	Mn	Mg	Fe	Ti	Zn	Sr	Al.
1	7.1	0.01	0.003	0.01	0.28	0.08	0.11	0.003	180 ppm	Bal.
2	8.2	2.5	0.7	0.01	0.31	0.16	0.12	0.003	184 ppm	Bal.
3	8.9	4.0	0.009	0.005	0.23	0.14	0.1	0.01	147 ppm	Bal.
4	9.4	3.5	0.8	0.02	0.33	0.15	0.10	0.003	181 ppm	Bal.
5	9.8	5.1	0.003	0.01	0.32	0.16	0.11	0.003	120 ppm	Bal.
6	10.5	1.8	1.5	0.02	0.35	0.14	0.13	0.003	150 ppm	Bal.
7	10.5	4.8	0.5	0.01	0.30	0.16	0.11	0.003	150 ppm	Bal.
8	11.6	4.5	0.003	0.02	0.25	0.16	0.12	0.003	184 ppm	Bal.
9	11.6	4.6	3.5	0.03	0.30	0.16	0.09	0.003	181 ppm	Bal.
10	11.7	4.9	0.004	0.01	0.27	0.17	0.10	0.003	120 ppm	Bal.
11	11.6	5.0	0.004	0.02	0.29	0.24	0.10	0.003	150 ppm	Bal.
12	11.7	5.4	0.003	0.02	0.24	0.25	0.10	0.003	130 ppm	Bal.
13	11.6	6.1	0.005	0.02	0.25	0.17	0.11	0.003	186 ppm	Bal.
14	11.8	4.9	0.004	0.01	0.24	0.13	0.1	0.001	135 ppm	Bal.
15	12.1	4.41	0.001	0.99	0.26	0.18	0.11	0.003	163 ppm	Bal.
16	14.2	4.2	0.003	0.02	0.24	0.25	0.10	0.003	130 ppm	Bal.
17	15.6	3.4	0.005	0.02	0.25	0.17	0.11	0.003	186 ppm	Bal.
18	16.8	2.2	0.001	0.02	0.26	0.18	0.11	0.003	163 ppm	Bal.

After heat treating the alloys listed in Table 1 as described hereinbefore, the alloys were examined as to microstructure. Basically the microstructure shows a large volume fraction of eutectic phase consisting of Si and Ni-rich phases present as fine (usually less than 5 micrometer in size) very uniformly distributed through aluminium matrix.

Mechanical characteristics of the high modulus alloys Nos. 1-16 under heat treatment condition (solid solutionising at 520 ℃ for 6 hours, followed by quenching within cold water, and ageing at 220 ℃ for 6 hours) are listed in Table 2. Young's modulus of the specimens was measured by a dynamic method namely an ultrasonic pulse technique according to ASTM E1875-13 standard and strength and elongation were measured according to the ASTM E8/E8M standard.

Table 2. Mechanical properties of the aluminium alloys of Table 1.

Alloy No.	Young's modulus (GPa) by tensile test	Young's modulus (GPa) by ultrasonic method	0.2% Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
1	74.1	74.2	104	222	10.7
2	79.2	80.1	230	260	4.5
3	84.2	84.1	202	264	4.6
4	81.2	82.6	235	265	3.8
5	86.1	88.6	244	273	3.1
6	81.5	83.2	238	282	4.1
7	87.2	89.1	240	275	2.8
8	88.2	86.2	186	252	2.6
9	90.1	87.8	242	270	0.7
10	90.1	90.1	231	288	2.7
11	89.8	88.8	224	292	2.6
12	91.1	89.2	223	297	2.4
13	92.4	92.1	228	286	1.9
14	89.2	88.1	218	290	3.6
15	93.7	90.3	222	281	1.3
16	88.7	90.1	223	274	1.5
17	87.3	89.1	243	256	1.7
18	89.1	90.2	233	278	0.9

Table 2 shows that the alloys of the present invention have a high Young's modulus compared to generally known aluminium alloys made by conventional melting and casting technology. The Young's modulus of the Al-Si-Ni alloys according to the invention is at least 80 GPa, and is mostly in the range of 88-94 GPa, significantly higher than that of the conventional cast Al alloy with ~70-74 GPa modulus. Without being bound by theory, the increase in modulus of more than 25 % is believed to be attributed to the presence of high modulus Si and Ni-rich phases.

Table 2 also demonstrates the tensile properties of the alloys. As seen, increased values in the yield strength (YS) and the ultimate tensile strength (UTS) is observed in the alloys of the invention by addition of Si, Ni and Cu elements. The YS and UTS are over 180 and 250 MPa, mostly over 220 and 280 MPa, respectively. The strength increment is understood to arise due to a secondary phase strengthening mechanism resulting from Si and Ni-rich phases as well as a precipitation strengthening mechanism formed by Mg and Cu elements in the alloys.

The reported data in literature show that for particulate reinforced cast aluminium alloys ductility is typically less than 0.5% when the Young's modulus is more than 85 GPa. However, it can be seen that the alloys according to the present invention may provide reasonable ductility, up to about 5.0%, when the Young's modulus reaches about ~90 GPa. The alloys of the invention therefore have significant potential for certain industrial applications where small elongation is not critical.

Example 2

Alloy No. 10 in Table 1 was prepared by a gravity casting route according to Example 1 experimental methods. In summary, the ingots were melted in a clay-graphite crucible using an electric resistance furnace. The alloying elements were added to the molten metal to obtain the required compositions, during which magnesium was added in the pure form, Si and Ni were added in the form of master alloys. The melt was poured at 730 ºC into a preheated permanent mould designed according to ASTM B-108. After preparing the alloy No. 10, it was heat treated under different heat treatment conditions, as shown in Table 3.

Table 3.	Solutionising temperature	Solutionising time	Aging temperature	Aging time
T4	530 ºC	8 h	-	-
T6	530 º C	8 h	180 ºC	8 h
T7	530 ºC	8 h	220 ºC	8 h
O	530 ºC	8 h	-	-

After the heat treatment under the conditions set out in Table 3, the microstructures of the alloys were examined. The microstructures showed a large volume fraction of eutectic phase consisting of Si and Ni-rich phases present as fine (usually less than 5 micrometer in size) uniformly distributed through the aluminium matrix. The microstructure under all heat treatment conditions was almost the same. However, larger precipitates were observed under T7 heat treatment compared with that of T6 condition.

The mechanical characteristics of the alloy No. 10 under different heat treatment conditions are listed in Table 4.

Table 4. Mechanical properties of alloy No. 10 under different heat treatment conditions

Heat treatment	Young's modulus (GPa) by tensile test	Young's modulus (GPa) by ultrasonic method	0.2% Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
T4	89.9	91.2	104	222	3.1
T6	89.2	90.8	260	292	2.1
T7	90.1	90.1	231	288	2.7
O	92.2	92.6	150	192	3.5

It is evident that the Young's modulus of alloy No. 10 is about 90 GPa, significantly higher than that of conventional aluminium alloys at a level of 70 GPa. This increase in Young's modulus of approximately 25 %, and hence the significant improvement, is understood to be due to the presence of high modulus Si and Ni-rich phases in the microstructure. As major phases of the hybrid alloys are constant, there are no significant changes of Young's modulus under different heat treatment conditions.

Table 4 also demonstrates the tensile properties of alloy No. 10 under different heat treatment conditions (i.e. T4, T6, T7 and O). As seen, a significant enhancement in the yield strength (YS) and the ultimate tensile strength (UTS) is observed in the alloy under T6 and T7 compared with T4 and O conditions. This significant improvement in the strength is understood to be attributed to the presence of precipitates. The YS and UTS are over 220 and 280 MPa, respectively, for T6 and T7 heat treatment conditions.

Although particular embodiments of the invention have been disclosed herein in detail, this has been done by way of example and for the purposes of illustration only. The aforementioned embodiments are not intended to be limiting with respect to the scope of the appended claims, which follow. It is contemplated by the inventors that various substitutions, alterations, and modifications may be made to the invention without departing from the spirit and scope of the invention as defined by the claims.

CLAIMS

1. An aluminium alloy for casting having a composition of:

    8.5-12.5 wt.% silicon as primary alloying element;

    2.5-9.0 wt.% nickel as secondary alloying element; at least two elements from the group of <3.5 wt.% copper, 0.1-0.8 wt.% magnesium, <1.0 wt.% manganese, <1.5 wt.% zinc, <1.0 wt.% beryllium, <1.0 wt.% lithium, <0.2 wt.% titanium, <0.2 wt.% vanadium, <0.2 wt.% silver, <0.2 wt.% niobium, <0.4 wt.% iron, <0.5 wt.% chromium, <0.2 wt.% zirconium; and

    0.001 to 0.05 wt.% of a nucleant selected from one or more of the group consisting of: TiB, TiB_2, AlB_2, B, NbB, NbB_2, TiC, and BC, with the balance being aluminium and inevitable impurities.

2. An alloy according to claim 1 having a composition of:

    9.0-12.0 wt.% silicon;

    3.5-7.0 wt.% nickel; and

    at least two elements from the group of 0.5-3.0 wt.% copper, 0.15-0.5 wt.% magnesium, <0.5 wt.% manganese, <1.0 wt.% zinc, <0.5 wt.% beryllium, <0.5 wt.% lithium, <0.15 wt.% titanium, <0.1 wt.% vanadium, <0.1 wt.% silver, <0.1 wt.% niobium, <0.2 wt.% iron, <0.3 wt.% chromium, <0.15 wt.% zirconium and

    0.001 to 0.05 wt.% of a nucleant selected from one or more of the group consisting of: TiB, TiB_2, AlB_2, B, NbB, NbB_2, TiC, and BC, with the balance being aluminium and inevitable impurities.

3. An alloy according to claim 1 or claim 2, further comprising from 10 to 3,000 ppm of a eutectic modifying agent selected from one or more of the group consisting of: strontium, sodium, antimony, yttrium, ytterbium and europeum.

4. Use of an aluminium alloy as described in any one of claims 1 to 3 in the manufacture of a cast product.

5. A cast product comprising the aluminium alloy of any one of claims 1 to 3, wherein the alloy is heat treated.

6. A cast product according to claim 5, wherein the alloy is heat treated after casting.

7. A cast product according to claim 6, wherein the alloy is heat treated after casting by solutionising the alloy at elevated temperature for a first period of time, followed by quenching with a quenching medium, followed by aging the alloy at a temperature lower than the solutionising elevated temperature but above ambient temperature for a further period of time.

8. A cast product according to claim 6 or claim 7, wherein the alloy is aged at a temperature of from 180-230 ^{0}C for about 1-100 hours.

9. A cast product according to any one of claims 6 to 8, wherein the alloy has a Young's modulus of at least about 80 GPa.

10. A cast product according to claim 9, wherein the alloy has a yield strength of at least 180 MPa and an ultimate tensile strength of at least 250 MPa.

11. A cast product according to any one of claims 6 to 10, wherein the alloy has a Young's modulus of about 80 GPa to about 95 GPa, a yield strength of from about 180 MPa to about 250 MPa, and an ultimate tensile strength of from about 250 MPa to about 300 MPa.

12. A cast product according to any one of claims 6 to 11, wherein the cast alloy is a vehicle component, optionally selected from one or more of the group consisting of: an engine component; a vehicle wheel; a steering wheel; a steering column; a frame member; and a gear box; a powertrain component; a chassis component; a body component and a transmission system.

13. A vehicle comprising the cast product of any one of claims 6 to 12, wherein the vehicle is selected from the group consisting of: an automobile; a motorcycle; a locomotive; a watercraft and an aircraft.

14. A method of forming a cast aluminium alloy product, comprising the steps of:

    forming an aluminium melt comprising 8.5 to 12.5 wt.% silicon as primary alloying element and 2.5 to 9.0 wt.% nickel as secondary alloying element;

    introducing the melt into a mould and solidifying the melt to form an as-cast alloy; and

heat treating the as-cast alloy to form the cast aluminium alloy product.

15. A method of forming a cast aluminium alloy product according to claim 14, method comprising the steps of:

forming an aluminium melt from 8.5 to 12.5 wt.% silicon as primary alloying element and 2.5 to 9.0 wt.% nickel as secondary alloying element, at least two elements from the group of: copper in an amount of 3.5 wt.% or less; magnesium in an amount of 0.1-0.8 wt.%; manganese in an amount of 1.0 wt.% or less; zinc in an amount of 1.5 wt.% or less; beryllium in an amount of 1.0 wt.% or less; lithium in an amount of 1.0 wt.% or less; titanium in an amount of 0.2 wt.% or less; vanadium in an amount of 0.2 wt.% or less; silver in an amount of 0.2 wt.% or less; niobium in an amount of 0.2 wt.% or less; iron in an amount of 0.4 wt.% or less; chromium in an amount of 0.5 wt.% or less; and zirconium in an amount of 0.2 wt.% or less; with the balance being aluminium and inevitable impurities;

optionally adding to the melt 10-3000 ppm of at least one eutectic modifying element selected from the group consisting of Sr, Na, Sb, Y, Yb, and Eu;

adding to the melt 0.001 to 0.05 wt.% of at least one nucleant selected from the group consisting of TiB, TiB_2, B, NbB, NbB_2, TiC, and BC;

introducing the melt into a mould and solidifying the melt to form an as-cast alloy; and

heat treating the as-cast alloy to form the cast aluminium alloy product.

Intellectual Property Office

Application No:	GB1817211.4	**Examiner:**	Matthew Lawson
Claims searched:	1-13	**Date of search:**	25 March 2019

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1-13	JP 2017115169 A (SHOWA) - WPI Abstract Accession No. 17-43690G and Alloys C & D of Table 1.
X	1-13	JPH01180938 A (RYOBI) - WPI Abstract Accession No. 89-246507 and No. 7 of Table 1.
X	1-13	US 4975243 A (SCOTT) - column 1 lines 55-67, column 2 lines 16-17 and column 3 lines 62-64.
X	1-13	US 5162065 A (SCOTT) - column 1 lines 50-51 & 54-59, column 2 lines 27-28 and column 3 lines 64-66
X	1-13	US 5055255 A (SCOTT) - column 1 lines 49-50 & 53-58, column 2 lines 25-26 and column 4 lines 3-5.
X	1-13	US 3297435 A (HANAFEE) - the whole document.

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
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Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

C22C

The following online and other databases have been used in the preparation of this search report

EPODOC, WPI, ALLOYS

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International Classification:

Subclass	Subgroup	Valid From
C22C	0021/02	01/01/2006
C22C	0021/00	01/01/2006
C22C	0021/04	01/01/2006
C22F	0001/043	01/01/2006