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(54) **ALUMINUM ALLOY MATERIAL**

(57) Provided is an aluminum alloy material including 1.2 atom% or more and 6.5 atom% or less of Fe, and 0.005 atom% or more and less than 0.15 atom% of one or more elements selected from the group consisting of Nd, W, and Sc, with the balance being Al and unavoidable impurities.

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Description

TECHNICAL FIELD

[0001] The present disclosure relates to an aluminum alloy material. The present application claims priority from Japanese Patent Application No. 2019-028568, which was filed on February 20, 2019, and all of the contents of the Japanese patent application are incorporated herein by reference.

BACKGROUND ART

[0002] Japanese Patent Laying-Open No. 06-158211 (Patent Literature 1) discloses an aluminum alloy containing Fe, a transition element such as Mn, Ni, and Cr, Si, and Mg. Japanese Patent Laying-Open No. 2000-096176 (Patent Literature 2) discloses an aluminum alloy containing 17% by weight or more of Si, Zr, and at least one selected from Y, mischmetal, and the like.

CITATION LIST

PATENT LITERATURE

[0003]

PTL 1: Japanese Patent Laying-Open No. 06-158211
PTL 2: Japanese Patent Laying-Open No. 2000-096176

SUMMARY OF INVENTION

[0004] A first aluminum alloy material of the present disclosure comprises:

1.2 atom% or more and 6.5 atom% or less of Fe; and
0.005 atom% or more and less than 0.15 atom% of one or more elements selected from the group consisting of Nd, W, and Sc,
with the balance being Al and unavoidable impurities.

[0005] A second aluminum alloy material of the present disclosure comprises:

1.2 atom% or more and 6.5 atom% or less of Fe;
0.005 atom% or more and less than 0.15 atom% of one or more first elements selected from the group consisting of Nd, W, and Sc; and
0.005 atom% or more and less than 2 atom% of one or more second elements selected from the group consisting of C and B,
with the balance being Al and unavoidable impurities.

DESCRIPTION OF EMBODIMENTS

[Problems to be Solved by the Present Disclosure]

[0006] An aluminum alloy material having excellent heat resistance, such as having a high tensile strength and/or high Vickers hardness even at a high temperature, is desirable.

[0007] The aluminum alloy described in Patent Literature 1 has a high tensile strength at 200°C, and has excellent heat resistance. However, when hot working as described in Patent Literature 1 is performed, precipitates such as compounds including Al and Fe tend to grow. The presence of coarse precipitates tends to make the aluminum alloy brittle. In order to prevent increased brittleness, the shape of the aluminum alloy material in hot working is restricted. Therefore, it is desirable that aluminum alloy materials having various shapes can be produced, that is, that the aluminum alloy material also has excellent production properties.

[0008] Further, the above-described transition elements such as Mn, Ni, and Cr have the action of making the above-described precipitates finer and increasing strength at a high temperature. However, the melting points of these transition elements are close to the melting point of Fe. As a result, it is difficult to separate Fe from the above transition elements when the aluminum alloy material is recycled. Therefore, it is desirable that the aluminum alloy material also has excellent

recycling operation properties.

[0009] The composition of the aluminum alloy described in Patent Literature 2 has a high amorphous formation ability. Therefore, the size of the compound that includes Al and Zr is nano-sized. The size of the Si crystallized product is about 100 nm. With such very fine particles, the aluminum alloy can have a high tensile strength and a high elongation at break at room temperature. Further, since the particles are very fine, the aluminum alloy is unlikely to become brittle even if the particles grow at a high temperature. However, the aluminum alloy has a large total added content of added elements. For example, in addition to Zr, 8% by weight (1 atom% to 2 atom%) of at least one selected from Y, mischmetal, and the like is included. Therefore, an aluminum alloy material having excellent heat resistance even if the amount of added elements is small is desired.

[0010] One of the objects of the present disclosure is to provide an aluminum alloy material having excellent heat resistance.

[Advantageous Effect of the Present Disclosure]

[0011] The aluminum alloy material of the present disclosure has excellent heat resistance.

[Description of Embodiments of the Present Disclosure]

[0012] First, the embodiments of the present disclosure will be listed and described.

(1) An aluminum alloy material according to one aspect of the present disclosure (hereinafter, sometimes referred to as the first Al alloy material) comprises:

1.2 atom% or more and 6.5 atom% or less of Fe (iron); and
0.005 atom% or more and less than 0.15 atom% of one or more elements selected from the group consisting of Nd (neodymium), W (tungsten), and Sc (scandium) (hereinafter, sometimes referred to as the first element), with the balance being Al (aluminum) and unavoidable impurities.

Although the total content of the added elements is small, the first Al alloy material has excellent heat resistance. One of the reasons for this is thought to be as follows.

The first Al alloy material that includes the first element together with Fe can have, for example, a structure in which fine particles composed of a compound that includes Al and Fe are dispersed in a fine crystal structure (as a specific example, see (2) below). Such a first Al alloy material has, for example, a high tensile strength and/or a high Vickers hardness at room temperature (e.g., 25°C). Therefore, the first Al alloy material tends to have a high tensile strength and/or a high Vickers hardness even at a high temperature, for example, 250°C. In particular, since the first Al alloy material includes the first element together with Fe, it is easy to maintain the above-described fine structure even at a high temperature (details are described later). From this fact as well, the first Al alloy material tends to have a high tensile strength and/or a high Vickers hardness even at the high temperature described above.

Further, the first Al alloy material has excellent production properties. This is because it is easy to obtain a material having excellent moldability as described later. In addition, as described later, the first Al alloy material also has excellent elongation, and it is easy to perform plastic working in both cold and warm conditions.

Moreover, the first Al alloy material has excellent recycling operation properties. This is because Al and Fe have different melting points and are easily separated. Further, since Al and Fe have a different melting point, reactivity to acid, and the like to that of the first element, these elements can be easily separated.

(2) An example of the Al alloy material of the present disclosure is an Al alloy material in which the first Al alloy material comprises a structure including a matrix that includes 99 atom% or more of Al and a particle that is present in the matrix and that is composed of a compound including Al and Fe (hereinafter, sometimes referred to as compound particle),

wherein in an arbitrary cross section of the first Al alloy material, an average grain size of crystal grains forming the matrix is 1700 nm or less and an average length of the compound particle is 140 nm or less.

The average grain size of the crystal grains and the average length of the compound particle are each the size measured in an arbitrary cross section of the Al alloy material. The details of the method for measuring the average grain size and the average length will be described in Test Example 1 described later. These points are the same for the configuration of (8) described later.

In the above mode, an effect of improving mechanical strength can be satisfactorily obtained as a result of a strengthening of the dispersion by the fine compound particle and a strengthening of the grain boundaries by the fine crystal grains. Further, since the fine compound particle is less likely to cause stress concentration, the fine compound

particle is less likely to be a starting point of cracking. From these facts, the above-described mode has, for example, a high tensile strength and/or a high Vickers hardness at room temperature. In particular, the first element is considered to have an action of stabilizing the compound particle even in a small amount. Due to the stabilization of the compound particle, the compound particle is less likely to become coarse (is less likely to grow into a needle shape) even at the above-described high temperature. Therefore, even at the high temperature, an increase in the brittleness of the Al alloy material due to the coarsening of the compound particle tends to be suppressed. In addition, since the compound particle tends to be maintained in a fine state, crystal growth is also suppressed. As a result, the above-described fine structure tends to be maintained even at the above-described high temperature. Therefore, the tensile strength and/or the Vickers hardness is less likely to decrease even at the above-described high temperature. Therefore, the above-described mode has excellent heat resistance. Further, since the above-described mode tends to have a fine structure even at a high temperature as described above, the degree of freedom of the shape in hot working is increased. In this respect, the above-described mode has excellent production properties.

(3) As an example of the first Al alloy material of (2), there can be mentioned a mode in which, in the cross section, when the area of a square region having a side length of 500 nm is taken as a unit area, an average number of the compound particles present per unit area is 10 or more and 220 or less.

The details of the method for measuring the average number will be described in Test Example 1 described later. This point is the same for the configuration of (9) described later.

In the above mode, it can be said that an appropriate amount of fine compound particle is included. Such a mode has better heat resistance because it is easier to obtain the above-described effects (strengthened dispersion, suppression of crystal growth, reduction in occurrence of cracks, suppression of increased brittleness, and the like) due to the fine compound particle.

(4) As an example of the first Al alloy material of (2) or (3), there can be mentioned a mode in which the compound particle has an aspect ratio of 3.5 or less.

The details of the method for measuring the aspect ratio will be described in Test Example 1 described later. This point is the same for the configuration of (10) described later.

When the compound particle has an aspect ratio of 3.5 or less, it is easier to obtain the above-described effects (strengthened dispersion, suppression of crystal growth, reduction in occurrence of cracks, suppression of increased brittleness, and the like) due to the fine compound particle. Therefore, the above mode has better heat resistance.

(5) As an example of the first Al alloy material, there can be mentioned a mode in which

a Vickers hardness at 25°C is 85 Hv or more, and
a temperature coefficient relating to a decrease in the Vickers hardness from 25°C to 250°C is 0.30%/°C or less.

The above mode has a high hardness at room temperature. Further, the above mode has excellent heat resistance in that the Vickers hardness does not easily decrease even at a high temperature such as 250°C.

(6) As an example of the first Al alloy material, there can be mentioned a mode in which an elongation at break at 25°C is 3% or more.

The above mode has a high toughness at room temperature. Such a mode is easy to bend and the like, and has excellent cold workability.

(7) An aluminum alloy material according to a separate aspect of the present disclosure (hereinafter, sometimes referred to as the second Al alloy material) comprises:

1.2 atom% or more and 6.5 atom% or less of Fe;
0.005 atom% or more and less than 0.15 atom% of one or more first elements selected from the group consisting of Nd, W, and Sc; and
0.005 atom% or more and less than 2 atom% of one or more second elements selected from the group consisting of C (carbon) and B (boron),
with the balance being Al and unavoidable impurities.

The second Al alloy material has excellent heat resistance for the same reasons as the first Al alloy material. Further, the second Al alloy material has excellent production properties and recycling operation properties for the same reason as the first Al alloy material.

In particular, as described later, the second Al alloy material has better heat resistance as a result of containing the second element. It is considered that the second element dissolves in solid solution in the matrix, thereby having an effect of improving the strength by strengthening the solid solution. Further, it is considered that the second element is present around the compound particle as a very fine carbide or boride, thereby suppressing the growth

of the compound particle. Therefore, even at the above-described high temperature, increased brittleness and crystal growth due to a coarse compound particle are more likely to be suppressed. As a result, the above-described fine structure is more easily maintained, and the heat resistance of the second Al alloy material is increased.

(8) As an example of the second Al alloy material, the second Al alloy material comprises a structure including a matrix that includes 99 atom% or more of Al and a particle (compound particle) that is present in the matrix and that is composed of a compound including Al and Fe,

wherein in an arbitrary cross section of the second Al alloy material, an average grain size of crystal grains forming the matrix is 1500 nm or less and an average length of the compound particle is 60 nm or less.

The crystal grains and compound particle of the above mode are finer than those of the first Al alloy material of (2) described above. Therefore, the above mode has better heat resistance because it is easier to obtain the above-described effects (strengthened dispersion, suppression of crystal growth, reduction in occurrence of cracks, suppression of increased brittleness, and the like) due to the fine compound particle, and easier to obtain strengthened grain boundaries due to the fine crystal grains.

(9) As an example of the second Al alloy material of (8), there can be mentioned a mode in which, in the cross section, when the area of a square region having a side length of 500 nm is taken as a unit area, an average number of the compound particles present per unit area is 40 or more and 530 or less.

The above mode can be said to include more of the finer compound particle than the mode of (3) described above. Such a mode has better heat resistance because it is easier to obtain the above-described effects (strengthened dispersion, suppression of crystal growth, reduction in occurrence of cracks, suppression of increased brittleness, and the like) due to the fine compound particle.

(10) As an example of the second Al alloy material of (8) or (9), there can be mentioned a mode in which the compound particle has an aspect ratio of 2.0 or less.

If the aspect ratio of the compound particle is 2.0 or less, it can be said that the compound particle has a shape closer to a sphere than the mode of (4) described above. Therefore, it is even easier for the above mode to obtain the above-described effects (strengthened dispersion, suppression of crystal growth, reduction in occurrence of cracks, suppression of increased brittleness, and the like) due to the fine compound particle. Therefore, the above mode has even better heat resistance.

(11) As an example of the first Al alloy material or the second Al alloy material, there can be mentioned a mode in which

a Vickers hardness at 25°C is 93 Hv or more, and

a temperature coefficient relating to a decrease in the Vickers hardness from 25°C to 250°C is 0.25%/°C or less.

The above mode has a higher hardness at room temperature than the mode of (5) described above. Further, the above mode has better heat resistance in that the Vickers hardness does not easily decrease even at a high temperature such as 250°C.

(12) As an example of the first Al alloy material or the second Al alloy material, there can be mentioned a mode in which an elongation at break at 25°C is 5% or more.

The above mode has higher toughness at room temperature than the mode of (6). Such a mode is easy to bend and the like, and has more excellent cold workability.

(13) As an example of the first Al alloy material or the second Al alloy material, there can be mentioned a mode in which a rate of decrease in tensile strength from 25°C to 250°C is less than 0.28%/°C.

[0013] The above mode has excellent heat resistance in that the tensile strength does not easily decrease even at a high temperature such as 250°C.

[Details of the Embodiments of the Present Disclosure]

[0014] Hereinafter, embodiments of the present disclosure will be described in detail.

<Aluminum alloy material>

(1) Overview

[0015] The aluminum alloy material (Al alloy material) of the embodiments is a molded body composed of an Al-based alloy mainly formed of Al (aluminum). This Al-based alloy includes a relatively large amount of Fe (iron), and also includes the following first element, or both the first element and a second element.

[0016] Specifically, the Al alloy material of a first embodiment has a composition that includes 1.2 atom% or more and

6.5 atom% or less of Fe (iron), and 0.005 atom% or more and less than 0.15 atom% of a first element, with the balance being Al (aluminum) and unavoidable impurities. The first element is one or more metallic elements selected from the group consisting of Nd (neodymium), W (tungsten), and Sc (scandium).

[0017] The Al alloy material of a second embodiment has a composition that includes 1.2 atom% or more and 6.5 atom% or less of Fe, 0.005 atom% or more and less than 0.15 atom% of the first element, and 0.005 atom% or more and less than 2 atom% of a second element, with the balance being Al and unavoidable impurities. The second element is one or more non-metallic elements selected from the group consisting of C (carbon) and B (boron).

[0018] For example, the Fe in the Al-based alloy is mainly present dispersed in a matrix as a fine precipitate. Further, for example, the matrix forming the Al-based alloy is composed of fine crystals.

[0019] The Al alloy materials of the embodiments composed of the above-described specific Al-based alloys not only have excellent strength, such as having a high tensile strength and/or Vickers hardness at room temperature (e.g., 25°C), but also tend to have a high tensile strength and/or high Vickers hardness at a high temperature (e.g., 250°C), and have excellent heat resistance.

[0020] This will now be described in more detail.

(2) Composition

(2-1) Fe

[0021] The Fe satisfies the following conditions (I) and (II).

(I) A solid solution amount (equilibrium state) with respect to the Al under conditions of 660°C and 1 atm is 0.5% by mass or less.

(II) The Fe forms a compound with Al. Among the binary intermetallic compounds of Al and Fe, the compound having the lowest element ratio of Fe (e.g., $Al_{13}Fe_4$) has a melting point of 1100°C or higher.

[0022] For example, as described later, if a molten metal of an Al-based alloy that includes Fe in the above-described specific range is quenched in the production process, the Fe dissolves in solid solution in the Al. However, based on the above (I) and (II), if the Al-based alloy in which the Fe is dissolved in solid solution is heated to a temperature at which Fe can be precipitated, the dissolved Fe turns into the above-described compound and precipitates in the matrix. The compound particle including the precipitated Fe is dispersed in the matrix. In the Al alloy material of the embodiments, the strengthening of the dispersion (precipitation strengthening) due to the compound particle can be used as one of the strengthening structures of the alloy.

[0023] The Fe content is 1.2 atom% or more and 6.5 atom% or less. When the Fe content is 1.2 atom% or more, the amount of the compound particle tends to increase. Therefore, the effect of improving the strength by strengthening the dispersion of the compound particle can be satisfactorily obtained. The Al alloy material of such an embodiment has superior strength and hardness at room temperature as well as better heat resistance as compared with the case where the Fe content is less than 1.2 atom% and the Fe is mainly dissolved in solid solution. The higher the Fe content, the higher the strength and hardness at room temperature, and the higher the heat resistance tends to be. From the viewpoint of improving heat resistance, the Fe content is preferably 1.4 atom% or more, more preferably 1.5 atom% or more, further preferably 2.0 atom% or more, still further preferably 2.5 atom% or more, and particularly preferably 3.0 atom% or more.

[0024] If the Fe content is 6.5 atom% or less, the compound particle is unlikely to be coarse and tends to be fine. Therefore, it is easy to obtain the effect of improving the strength by strengthening the dispersion of the fine compound particle. In addition, the fine compound particle tends to suppress crystal growth. If the crystal grains are fine, the effect of improving the strength by strengthening the grain boundaries can be easily obtained. Moreover, the fine compound particle is unlikely to be the starting point of cracking. In addition, if the compound particle is fine, the compound particle is unlikely to become coarse even at a high temperature. Therefore, the increased brittleness of the Al-based alloy due to the coarse compound particle tends to be suppressed. From these facts, strength and hardness at room temperature are excellent, and tensile strength and/or Vickers hardness tend to be high even at a high temperature. In addition, by reducing the occurrence of cracks, elongation tends to be high. Further, if the Fe content is low to a certain extent, it is easy to produce the Al alloy material. This is because it is easy to obtain a material having excellent moldability in the production process. The smaller the Fe content, the less likely the compound particle is to become coarse. Due to the fineness of the compound particle, the Al alloy material has excellent heat resistance. From the viewpoint of obtaining good heat resistance and the like, the Fe content is preferably 6.2 atom% or less, more preferably 6.0 atom% or less, further preferably 5.5 atom% or less, still further preferably 5.0 atom% or less, and particularly preferably 4.5 atom% or less.

[0025] The melting point of Fe is higher than the melting point of Al. Therefore, the two can be easily separated. In

this respect, the Al alloy material of the embodiments has excellent recyclability.

(2-2) First element

[0026] When the Al alloy material includes the first element in the range of 0.005 atom% or more and less than 0.15 atom%, for example, the first element is considered to be mainly included in the above-described compound particle. In this case, the first element is considered to promote the generation of fine precipitate cores. Therefore, the compound including Al and Fe tends to finely precipitate. Further, the first element is thought to have an action of stabilizing the compound. Although the details of the stabilization mechanism are unknown, the fact that the compound becomes thermodynamically stable is shown from calculations of the phase diagram. Due to the stabilizing action, even at a high temperature, for example, 200°C or higher, and further 250°C, the compound particle is less likely to become coarse and can easily maintain a fine state. As a result, even at the high temperature described above, the effects such as the effect of improving the strength by strengthening the dispersion, the effect of improving the strength by strengthening the grain boundaries, and the suppression of increased brittleness, can be easily obtained as described above. Therefore, the Al alloy material of the embodiments in which the first element is included in a specific range together with Fe not only has excellent strength and hardness at room temperature, but also has excellent heat resistance.

[0027] If the content of the first element is 0.005 atom% or more, the compound particle is stable and is unlikely to grow. The higher the content of the first element, the more difficult it is for the compound particle to grow, and as a result, heat resistance is increased. From the viewpoint of improving heat resistance, the content of the first element is preferably 0.006 atom% or more, more preferably 0.008 atom% or more, further preferably 0.010 atom% or more, and still further preferably 0.015 atom% or more.

[0028] If the content of the first element is less than 0.15 atom%, the Al alloy material has excellent strength and hardness, and also has high elongation. From the viewpoint of improving toughness, the content of the first element is preferably 0.14 atom% or less, more preferably 0.12 atom% or less, further preferably 0.10 atom% or less, still further preferably 0.08 atom% or less.

[0029] The Al alloy material of the embodiments may include only one element among Nd, W, and Sc as the first element, or may include two or three of those elements. When two or three of those elements are included, the above-described content of the first element is the total amount thereof.

[0030] Among the first elements, the above-described stabilizing effect is considered to be more easily obtained in the order of Sc, Nd, and W. Further, when Nd and/or Sc is included as the first element, the production properties of the Al alloy material are also excellent. The melting point of Nd is lower than the melting point of Fe. The melting point of Sc is close to the melting point of Fe. Therefore, it is easy to obtain molten metal in the production process. The low eutectic temperature of Nd or Sc and Al is also advantageous from a production perspective.

[0031] In the Al alloy material of the embodiments, a part of the first element may be present as a compound that includes Al but does not include Fe, typically, an intermetallic compound of the first element and Al. Examples of the intermetallic compound of the first element and Al include Al_4Nd, Al_3Sc, and Al_4W. The melting point of these intermetallic compounds is over 1100°C. The intermetallic compound tends to exist more stably as a precipitate as compared with the above-described binary intermetallic compound including Al and Fe. With the precipitate, an effect of improving the strength by precipitation strengthening can be expected. This effect by precipitation strengthening is considered to be more easily obtained in the order of W, Nd, and Sc.

(2-3) Second element

[0032] The Al alloy material of Embodiment 2 that includes a second element tends to have better strength and hardness at room temperature, as well as heat resistance, than the Al alloy material of Embodiment 1 that does not include the second element. The reasons for this are as follows.

[0033] When the Al alloy material includes the second element in the range of 0.005 atom% or more and less than 2 atom%, the second element is thought to be mainly present as extremely fine carbides or borides around the compound particle, or in the matrix as a solid solution. It is considered that the carbides and borides suppress the diffusion of Fe in the compound particle, and which tends to suppress the coarsening of the compound particle, and particularly growth into a needle shape. If the compound particle is fine, as described above, it is easier to obtain the effects such as a strengthened dispersion, suppression of crystal growth, and even strengthened grain boundaries, a reduction in the occurrence of cracks due to the coarse compound particle, and suppression of increased brittleness. When the second element is dissolved in solid solution in the matrix, it is considered that the effect of improving the strength by strengthening the solid solution can be obtained.

[0034] When the content of the second element is 0.005 atom% or more, the effects of the compound particle being a fine particle is more easily obtained. The higher the content of the second element, the easier it is to obtain the above-described effects. As a result, heat resistance tends to be high. Further, the higher the content of the second element,

the easier it is to suppress a decrease in toughness. From the viewpoint of further improving heat resistance and obtaining good toughness and the like, the content of the second element is preferably 0.008 atom% or more, more preferably 0.010 atom% or more, and further preferably 0.050 atom% or more.

[0035] If the content of the second element is less than 2 atom%, the Al alloy material has excellent strength and hardness, and also has high elongation. From the viewpoint of further improving toughness and the like, the content of the second element is preferably 1.5 atom% or less, more preferably 1.2 atom% or less, further preferably 1.0 atom% or less, and still further preferably 0.5 atom% or less. The Al alloy material of Embodiment 2 includes the second element in addition to the first element, but the content of the second element is less than 2 atom%. Therefore, the Al alloy material of Embodiment 2 has excellent heat resistance, even though the content of the added elements is smaller than that of the aluminum alloy described in Patent Literature 2.

[0036] The Al alloy material of the embodiments may include only one element of C and B as the second element, or may include two elements. When two elements are included, the above-described content of the second element is the total amount thereof.

[0037] When C is included as the second element, the effect of improving toughness tends to be higher than when B is included. When B is included as the second element, heat resistance tends to be better than when C is included. By including both C and B, it is expected that the balance between heat resistance and toughness can be adjusted.

[0038] The second element and the first element differ from Al and Fe in melting point, reactivity to acid, and the like. Therefore, it is possible to easily separate Al and Fe from the first element and the second element. In this respect, the Al alloy material of the embodiments has excellent recyclability.

(2-4) Other points

[0039] The Fe content, the first element content, and the second element content described here are atomic ratios when the Al-based alloy forming the Al alloy material is 100 atom%. The above content refers to the amount contained in the Al-based alloy. When the raw material (typically aluminum bullion) includes Fe, the first element, and the second element as impurities, in the production process, it is preferable to adjust the added amounts of the elements such as Fe added to the raw material so that the content of the elements such as Fe satisfies the above-described ranges.

[0040] Hereinafter, unless specified otherwise, the Al alloy material of Embodiment 1 that includes the first element but does not include the second element and the Al alloy material of Embodiment 2 that includes the first element and the second element will be described together.

(3) Structure

[0041] The Al alloy material of the embodiments comprises a structure including, for example, a matrix that includes 99 atom% or more of Al and a particle (compound particle) that is composed of a compound including Al and Fe. The compound particle is present in the matrix. In the Al alloy material of Embodiment 1, in an arbitrary cross section of the Al alloy material, the average grain size of the crystal grains forming the matrix is 1700 nm or less. Further, in the cross section, the average length of the compound particle is 140 nm or less. In the Al alloy material of Embodiment 2, in an arbitrary cross section of the Al alloy material, the average grain size of the crystal grains forming the matrix is 1500 nm or less. Further, in the cross section, the average length of the compound particle is 60 nm or less.

(3-1) Matrix

[0042] In the Al alloy material of the embodiments, the matrix is the main phase excluding precipitates such as compounds including Al and Fe. When the matrix is 100 atom%, if the Al content in the matrix is 99 atom% or more, it can be said that the solid solution amount of Fe is small. Further, if the Al content in the matrix is 99 atom% or more, it can be said that the Fe in the Al alloy material is substantially present as precipitates. Such an Al alloy material has a good effect of improving the strength by strengthening the dispersion of the compound particle, and has excellent heat resistance. Further, in such an Al alloy material, the strength and hardness at room temperature are also increased. The higher the content of Al, the smaller the solid solution amount of Fe and the higher the heat resistance. From the viewpoint of further improving the heat resistance, the content of the Al is preferably 99.2 atom% or more, and more preferably 99.5 atom% or more. It is preferable to adjust the amount of the added elements such as Fe, the production conditions, and the like so that the content of the Al is within a predetermined range.

(3-2) Crystal grains

[0043] In an arbitrary cross section of the Al alloy material, if the average grain size of the crystal grains of the matrix is 1700 nm or less, it can be said that the crystals are small. Small crystal grains mean that there are many grain

boundaries. If there are many grain boundaries, the slip surface tends to be discontinuous through the grain boundaries. As a result, the resistance to slipping is increased. This improvement in resistance strengthens the grain boundaries. Thus, in an Al alloy material having a matrix with a fine crystal structure, grain boundary strengthening can be employed as a structure for strengthening the alloy.

[0044] The average grain size of the crystal grains of the matrix is defined here as, in the cross section, the diameter of a circle having an area equivalent to the cross-sectional area of the crystal grains, and is obtained by averaging the grain sizes of a plurality of crystal grains. The details of the measurement method will be described in Test Example 1.

[0045] The smaller the average grain size of the crystal grains of the matrix, the easier it is to obtain the effect of improving the strength by strengthening the grain boundaries. Further, the smaller the crystal grains, the easier it is for the fine compound particle to be uniformly dispersed in the matrix. Therefore, it is also easy to obtain the effect of improving the strength by strengthening the dispersion of the fine compound particle. Due to these strength improving effects, the heat resistance of the Al alloy material is increased. Due to these strength improving effects, the strength and hardness of the Al alloy material at room temperature are also increased. From the viewpoint of improving heat resistance and the like, the average grain size is preferably 1600 nm or less, more preferably 1500 nm or less, and further preferably 1450 nm or less.

[0046] In the Al alloy material of Embodiment 2 that includes the first element and the second element, if the average grain size of the crystal grains of the matrix is 1500 nm or less, the effect of improving the strength by strengthening the grain boundaries can be more easily obtained, and by extension, the heat resistance of the Al alloy material is further increased. The average grain size is preferably 1450 nm or less, more preferably 1400 nm or less, further preferably 1350 nm or less, and still further preferably 1300 nm or less. In particular, when the average grain size is 1250 nm or less, and further 1200 nm or less, 1000 nm or less, 900 nm or less, or 800 nm or less, the heat resistance of the Al alloy material is further increased.

[0047] The lower limit of the average grain size of the crystal grains of the matrix is not particularly limited. Considering production properties and the like, the average grain size is, for example, 200 nm or more, preferably 250 nm or more, and more preferably 300 nm or more.

(3-3) Compound particle

(3-3-1) Size of compound particle

[0048] In an arbitrary cross section of the Al alloy material, if the average length of the compound particle is 140 nm or less, the compound particle is not continuous in the matrix, and can be said to be short (small). The fine compound particle tends to be present alone in the matrix, that is, the fine compound particle tends to be present in a dispersed manner. The strength and hardness of the Al alloy material are increased by the strengthening of the dispersion by the fine compound particle.

[0049] As used herein, the average length of the compound particle is the average value obtained by averaging the maximum lengths of each compound particle in the cross section. The details of the measurement method will be described in Test Example 1.

[0050] The shorter the average length of the compound particle, the easier it is to obtain the effect of improving the strength by strengthening the dispersion. Further, when the compound particle is fine, as described above, it is easy to obtain the effects of suppressing crystal growth, and by extension an improvement in the strength by strengthening of the grain boundaries, a reduction in the occurrence of cracks, suppression of increased brittleness, and the like. Therefore, the heat resistance of the Al alloy material is increased. Further, if the compound particle is fine, the strength and hardness of the Al alloy material at room temperature can also be increased. From the viewpoint of improving heat resistance and the like, the average length is preferably 120 nm or less, more preferably 100 nm or less, and further preferably 80 nm or less. When the average length is 50 nm or less, the heat resistance of the Al alloy material is further increased.

[0051] In the Al alloy material of Embodiment 2 that includes the first element and the second element, if the average length of the compound particle is 60 nm or less, the effect of improving the strength by strengthening the dispersion can be more easily obtained, and by extension, the heat resistance of Al alloy material is further increased. When the average length is 55 nm or less, further 50 nm or less, 45 nm or less, or 40 nm or less, the heat resistance of the Al alloy material is even further increased.

[0052] The lower limit of the average length of the compound particle is not particularly limited. Considering production properties and the like, the average length is, for example, 10 nm or more, and preferably 15 nm or more.

(3-3-2) Amount of compound particle present

[0053] The presence of an appropriate amount of the fine compound particle makes it easy to obtain the above-described effects, such as strengthening the dispersion, suppressing crystal growth, reducing the occurrence of cracks,

and suppressing increased brittleness. In the Al alloy material of Embodiment 1 that includes the first element but does not include the second element, the average number of the compound particles is, for example, 10 or more and 220 or less. In the Al alloy material of Embodiment 2 that includes the first element and the second element, since the compound particle is finer as described above, more of the compound particle is likely to be present. For example, in the Al alloy material of Embodiment 2, the average number of the compound particles is 40 or more and 530 or less.

[0054] The average number of the compound particles is defined herein as follows. In an arbitrary cross section of the Al alloy material, a square region having a side length of 500 nm is set as a unit area. The average value of the number of the compound particle present per unit area is defined as the average number of the compound particles per unit area. The details of the measurement method will be described in Test Example 1.

[0055] If the average number of the compound particles per unit area is 10 or more, the effects of the fine compound particle (strengthened dispersion, suppression of crystal growth, reduction of cracking, suppression of increased brittleness, and the like) can be easily obtained. As a result, the heat resistance of the Al alloy material is increased. The higher the average number, the more the heat resistance tends to improve. From the viewpoint of improving heat resistance and the like, the average number is preferably 12 or more, and more preferably 15 or more. When the average number is 20 or more, and further 25 or more, the heat resistance of the Al alloy material is further increased.

[0056] In the Al alloy material of Embodiment 2 that includes the first element and the second element, if the average number of the compound particles per unit area is 40 or more, the above-described effects of the fine compound particle tend to be obtained more easily, and the heat resistance of the Al alloy material is further increased. When the average number is 45 or more, and further 60 or more, the heat resistance of the Al alloy material is further increased.

[0057] The higher the average number of the compound particles per unit area, the better the heat resistance of the Al alloy material tends to be. However, the higher the average number of the compound particles per unit area, the more the elongation of the Al alloy material tends to decrease. In the Al alloy material of the Embodiment 1 that includes the first element but does not include the second element, if the average number is 220 or less, the heat resistance is excellent and the elongation is high. From the viewpoint of improving toughness and the like, the average number is preferably 200 or less, and more preferably 180 or less. When the average number is 100 or less, the elongation of the Al alloy material can be further increased.

[0058] In the Al alloy material of Embodiment 2 that includes the first element and the second element, if the average number of the compound particles per unit area is 530 or less, the heat resistance is excellent and the elongation is high. From the viewpoint of improving toughness and the like, the average number is preferably 400 or less, more preferably 350 or less, and further preferably 300 or less. When the average number is 200 or less, the elongation of the Al alloy material can be further increased.

[0059] In an arbitrary cross section of the Al alloy material, if the average number of the compound particles per unit area satisfies the above-described range, it can be said that the anisotropy of the abundance of compound particles is small or substantially nonexistent. That is, the compound particle is uniformly dispersed.

(3-3-3) Compound particle shape

[0060] Rather than a very elongated shape such as a needle shape, the shape of the compound particle is preferably an ellipse with a small difference between the major axis length and the minor axis length, and more preferably as close to a spherical shape as possible. This is because the compound particle is more likely to be uniformly dispersed in the matrix. Further, the compound particle is unlikely to be the starting point of cracking. For example, the aspect ratio of the compound particle is 3.5 or less. In the Al alloy material of Embodiment 2 that includes the first element and the second element, as described above, the compound particle is unlikely to be coarse (needle-shaped). Therefore, the aspect ratio of the compound particle is, for example, 2.0 or less.

[0061] As used herein, the aspect ratio here is the ratio of the major axis length to the minor axis length (major axis length / minor axis length). The major axis length is the maximum length of the compound particle. The minor axis length is the length of the compound particle in the direction orthogonal to the major axis direction, and is the maximum length among those lengths. The details of the measurement method will be described in Test Example 1.

[0062] If the aspect ratio of the compound particle is 3.5 or less, the compound particle tends to be uniformly dispersed and is unlikely to be the starting point of cracking. Therefore, both the strength and elongation of the Al alloy material at room temperature are increased, and the heat resistance also tends to be increased. It can be said that the closer the aspect ratio is to 1, the anisotropy of the shape is smaller or substantially eliminated. Such a compound particle tends to be uniformly dispersed in the matrix. As a result, the heat resistance, and the like of the Al alloy material tends to be improved. From the viewpoint of improving heat resistance and the like, the aspect ratio is preferably 3.3 or less, more preferably 3.0 or less, and further preferably 2.8 or less.

[0063] In the Al alloy material of Embodiment 2 that includes the first element and the second element, if the aspect ratio of the compound particle is 2.0 or less, the strength and hardness of the Al alloy material at room temperature and the elongation are increased, and heat resistance is also increased. From the viewpoint of improving heat resistance

and the like, the aspect ratio is preferably 1.9 or less, more preferably 1.8 or less, and further preferably 1.7 or less.

(4) Relative density of the Al alloy material

[0064] The Al alloy material of the embodiments can have a relative density of, for example, 90% or more. Such a dense Al alloy material has few pores that can serve as the starting point of cracking. As a result, not only the strength and toughness of the Al alloy material at room temperature are increased, but also the heat resistance is increased. From the viewpoint of improving heat resistance and the like, the relative density is preferably 92% or more, more preferably 93% or more, and further preferably 95% or more. The upper limit of the relative density is 100%. If the relative density is 100%, the Al alloy material has a true density. The details of the method for measuring the relative density will be described in Test Example 1.

(5) Mechanical properties of the Al alloy material

(5-1) Tensile strength

[0065] The Al alloy material of the embodiments has, for example, a tensile strength at 25°C of 250 MPa or more. The Al alloy material of Embodiment 2 that includes the first element and the second element tends to have a higher tensile strength. For example, in the Al alloy material of Embodiment 2, the tensile strength at 25°C is 270 MPa or more. If the tensile strength at room temperature is high, the Al alloy material tends to have a high tensile strength to some extent even if the tensile strength decreases at a high temperature, for example, 250°C. Such an Al alloy material not only has excellent strength at room temperature, but also has excellent heat resistance.

[0066] When the tensile strength at 25°C is 280 MPa or more, and further 300 MPa or more, the Al alloy material has even better strength at room temperature and heat resistance.

[0067] When the tensile strength at 25°C is, for example, 550 MPa or less, and further 500 MPa or less, the elongation of the Al alloy material is unlikely to decrease, and the elongation is also excellent.

(5-2) Vickers hardness

[0068] The Al alloy material of the embodiments has, for example, a Vickers hardness at 25°C of 85 Hv or more. If the Vickers hardness is 85 Hv or more, the hardness at room temperature is high, so that the strength at room temperature also tends to be high. Further, since the Vickers hardness at room temperature is high, the Al alloy material tends to have a high Vickers hardness to some extent even if the Vickers hardness decreases at a high temperature, for example, 250°C. Therefore, the strength of the Al alloy material also tends to be high to some extent. Such an Al alloy material also has excellent heat resistance. The Al alloy material of Embodiment 2 that includes the first element and the second element tends to have a higher Vickers hardness. For example, in the Al alloy material of Embodiment 2, the Vickers hardness at 25°C can be 93 Hv or more.

[0069] The Al alloy material of Embodiment 1 that includes the first element but does not include the second element has even better hardness and strength at room temperature and heat resistance when the above-described Vickers hardness is 86 Hv or more, and further 88 Hv or more.

[0070] When the Vickers hardness at 25°C is 95 Hv or more, and further 100 Hv or more, the Al alloy material has even better hardness and strength at room temperature and heat resistance.

[0071] When the Vickers hardness at 25°C is, for example, less than 165 Hv, further 162 Hv or less and 150 Hv or less, the elongation of the Al alloy material is unlikely to decrease, and the elongation is also excellent.

(5-3) Elongation at break

[0072] In the Al alloy material of the embodiments, when Fe precipitates as described above, the matrix tends to exhibit a ductile behavior. Further, in the Al alloy material of the embodiments, when Fe precipitates as described above, the fine compound particle is unlikely to be the starting point of cracking. Therefore, the Al alloy material of the embodiments tends to have a high elongation.

[0073] The Al alloy material of the embodiments has, for example, an elongation at break at 25°C of 3% or more. If the elongation at break is 3% or more, the Al alloy material has excellent toughness at room temperature. The Al alloy material of the embodiments, which has excellent strength and toughness at room temperature, has excellent plastic workability at a cold temperature. Such an Al alloy material can be used, for example, as a material for cold working. In the Al alloy material of Embodiment 2 that includes the first element and the second element, as described above, the compound particle tends to be finer and there tends to be an increased number of the compound particle due to the second element. Therefore, in the Al alloy material of Embodiment 2, the strength and hardness tend to be increased

by the effect of an improvement in strength by strengthening the dispersion and the grain boundaries, and each compound particle is unlikely to be the starting point of cracking, and good elongation can be easily obtained. Therefore, the Al alloy material of Embodiment 2 tends to have a higher elongation at break. For example, in the Al alloy material of Embodiment 2, the elongation at break at 25°C is 5% or more.

[0074] In the Al alloy material of Embodiment 1 that includes the first element but does not include the second element, if the elongation at break is 3.5% or more, and further 4.0% or more, 4.5% or more, or 5.0% or more, toughness is better.

[0075] When the elongation at break at 25°C is 5.5% or more, and further 6.0% or more or 6.5% or more, the Al alloy material has even better toughness.

[0076] When the elongation at break at 25°C is, for example, 30% or less, and further 25% or less, the tensile strength and Vickers hardness of the Al alloy material are unlikely to decrease, and it is easy to maintain the high strength and hardness at room temperature and the high heat resistance.

(5-4) Heat resistance

(5-4-1) Rate of decrease in tensile strength

[0077] The Al alloy material of the embodiments has excellent heat resistance, and the tensile strength does not easily decrease even at a high temperature, for example, 250°C. Quantitatively, a rate of decrease K_{TS} in tensile strength from 25°C to 250°C is, for example, less than 0.28%/°C. The rate of decrease K_{TS} (%/°C) is a value obtained from the following formula.

$$\text{Rate of decrease } K_{TS} = [(T_r - T_h) / \{(250-25) \times T_r\}] \times 100$$

[0078] T_r is the tensile strength (MPa) at 25°C, and T_h is the tensile strength (MPa) at 250°C.

[0079] If the rate of decrease K_{TS} is less than 0.28%/°C, the amount of decrease in tensile strength is small even at 250°C, and the Al alloy material tends to have a high tensile strength. Such an Al alloy material has excellent heat resistance. When the rate of decrease K_{TS} is 0.27%/°C or less, and further 0.26%/°C or less or 0.25%/°C or less, the amount of decrease in tensile strength is smaller, and the Al alloy material has better heat resistance.

[0080] In the Al alloy material of Embodiment 2 that includes the first element and the second element, as described above, the tensile strength at room temperature tends to be high. Therefore, the smaller the rate of decrease K_{TS} is, the higher the tensile strength tends to be, and the better the heat resistance is, which is preferable. For example, the rate of decrease K_{TS} is 0.24%/°C or less, and preferably 0.23%/°C or less.

(5-4-2) Temperature coefficient of Vickers hardness

[0081] The Al alloy material of the embodiments has excellent heat resistance, and the Vickers hardness does not easily decrease even at a high temperature, for example, 250°C. Quantitatively, a temperature coefficient K_{Hv} of the decrease in Vickers hardness from 25°C to 250°C is, for example, 0.30%/°C or less. The temperature coefficient K_{Hv} (%/°C) is a value obtained from the following formula.

$$\text{Temperature coefficient } K_{Hv} = [(H_r - H_h) / \{(250-25) \times H_r\}] \times 100$$

[0082] H_r is the Vickers hardness (H_v) at 25°C, and H_h is the Vickers hardness (H_v) at 250°C.

[0083] When the temperature coefficient K_{Hv} is 0.30%/°C or less, the amount of decrease in Vickers hardness is small even at 250°C, and the Al alloy material tends to have a high Vickers hardness. Such an Al alloy material has excellent heat resistance. When the temperature coefficient K_{Hv} is 0.29%/°C or less, and further 0.28%/°C or less or 0.27%/°C or less, the amount of decrease in Vickers hardness is small, and the Al alloy material has better heat resistance. It is more preferable that the Al alloy material has a Vickers hardness of 85 H_v or more at 25°C and a temperature coefficient K_{Hv} of 0.30%/°C or less.

[0084] In the Al alloy material of Embodiment 2 that includes the first element and the second element, as described above, the Vickers hardness at room temperature tends to be high. Therefore, the smaller the temperature coefficient K_{Hv} is, the higher the Vickers hardness of the Al alloy material tends to be, and the better the heat resistance is, which is preferable. In the Al alloy material of Embodiment 2, the temperature coefficient K_{Hv} is, for example, 0.25%/°C or less. When the temperature coefficient K_{Hv} is 0.24%/°C or less, and further 0.23%/°C or less, the Al alloy material has even better heat resistance, which is preferable. It is more preferable that the Al alloy material of Embodiment 2 has a Vickers hardness of 93 H_v or more at 25°C and a temperature coefficient of 0.25%/°C or less.

[0085] The average grain size of the crystal grains, the average length of the compound particle, the average number, and the tensile strength, Vickers hardness, and elongation at break of the Al alloy material can be changed by, for example, adjusting the Fe content, the content of the first element, the content of the second element, the relative density, the production conditions, and the like. For example, when Fe is large in the range described above, the average grain size, the average length, and the average number tend to be larger. When Fe is small in the range described range, those properties tend to be the opposite. Further, when Fe is large in the range described above, the tensile strength and Vickers hardness tend to increase, and when Fe is small in the range described above, elongation at break tends to increase.

(6) Usage modes of the Al alloy material

[0086] The Al alloy material of the embodiments can have various shapes and sizes depending on the shape of a mold and/or cutting or plastic working applied to the Al alloy material after molding. For example, examples of the Al alloy material of the embodiments include a solid substance typified by a bar material, a wire material, and a plate material, a cylinder having a through hole, and the like. Since the Al alloy material of the embodiments has excellent heat resistance, it can be utilized as a product capable of being used in a high temperature environment (e.g., 200°C to 250°C). The Al alloy material of the embodiments can be utilized as a product used at room temperature because, as described above, it has excellent mechanical properties at room temperature. Moreover, since the Al alloy material of the embodiments has excellent plastic workability as described above, it can be utilized as a material to be subjected to plastic working, such as forging, extrusion, wire drawing, and rolling. When utilized as such a material, the degree of freedom of the shape is high, and it is easy to produce products having various shapes. In this respect, the Al alloy material of the embodiments also has excellent production properties.

(7) Main effects

[0087] The Al alloy material of the embodiments has excellent heat resistance. In addition, the Al alloy material of the embodiments has excellent strength and hardness at room temperature, as well as toughness. These effects will be specifically described in Test Example 1 described later.

<Production method of Al alloy material>

(1) Overview

[0088] The Al alloy material of the embodiments can be produced, for example, by a production method including the following steps.

[First Step]

[0089] A molten metal composed of an Al-based alloy having the following first composition or an Al-based alloy having the following second composition is quenched to produce a powdery material or a flaky material.

- First composition: 1.2 atom% or more and 6.5 atom% or less of Fe, and 0.005 atom% or more and less than 0.15 atom% of the above-described first element, with the balance being Al and unavoidable impurities.
- Second composition: 1.2 atom% or more and 6.5 atom% or less of Fe, 0.005 atom% or more and less than 0.15 atom% of the above-described first element, and 0.005 atom% or more and less than 2 atom% of the above-described second element, with the balance being Al and unavoidable impurities.

[Second step]

[0090] Using the above-described material, an intermediate material having a relative density of 85% or more is produced under conditions of a temperature equal to or less than the temperature at which the compound including Al and Fe does not precipitate.

[Third step]

[0091] Using the above-described intermediate material, a molded body having a predetermined shape is produced under conditions of a temperature equal to or more above the temperature at which the above-described compound precipitates.

[0092] By quenching the molten metal that includes the first element together with Fe, the Fe is dissolved in solid solution, a solidified material is obtained in which the compound including Al and Fe is substantially not precipitated, or a fine solidified material is obtained in which the compound is not coarse even if the compound is precipitated. Moreover, since quenching is carried out, the crystal grains are also fine. Such a material has excellent moldability, and therefore a dense intermediate material can be satisfactorily produced. Further, when molding the intermediate material, the precipitated compound and crystal grains tend to be maintained in a fine state. As a result, the compound and crystal grains tend to be fine even in subsequent processes. Further, when the molded body is formed into a predetermined shape, the fine compound particle can be more reliably precipitated while being able to be satisfactorily molded into the predetermined shape. Crystal growth can also be suppressed by the fine compound particle. As a result of these matters, it is possible to produce an Al alloy material, typically an Al alloy material of Embodiment 1 or Embodiment 2, in which a fine particle composed of the above-described compound is dispersed in a fine crystal structure. Further, due to the fact that a material having excellent moldability is used, the fact that the number of steps is small, and the like, this production method can produce an Al alloy material having an above-described fine structure, typically the Al alloy material of Embodiment 1 or Embodiment 2, with high productivity.

[0093] Hereinafter, each step will be described.

(2) First step: Production of material

(2-1) Overview

[0094] In this step, by quenching a molten metal composed of the above-described Al-based alloy, typically, compounds including Al and Fe (e.g., $Al_{13}Fe_4$ type or Al_6Fe type) substantially do not precipitate, and a material (e.g., a supersaturated solid solution) in which Fe is substantially dissolved in solid solution in Al is obtained. Alternatively, a material in which a fine particle composed of the above-described compound is precipitated can be obtained. Here, the solidification rate of the molten metal in conventional continuous casting method is 1000 °C/sec or less, although this is faster than in the case of using a fixed casting mold. The practical speed is even slower. If the solidification rate of the molten metal including 1.2 atom% or more, and further 1.4 atom% or more, of Fe is 1000 °C/sec or less, the above-described compound is precipitated as a coarse particle in the cast material. For example, a coarse compound particle may be produced having the average length of 1000 nm or more. Such a coarse compound particle is likely to act as a starting point of cracking. Further, the crystal grains tend to be large. For example, the average grain size may be 2000 nm or more, and further 3000 nm or more. Not only is a coarse compound particle present, but the crystal grains are large, and therefore the obtained cast material has poor moldability. In the embodiments, in view of the relatively large amount of Fe of 1.2 atom% or more, the solidification rate of the molten metal is set higher than the solidification rate in the above-described conventional continuous casting method. In particular, the solidification rate (cooling rate) is preferably 1×10^5 °C/sec (100,000 °C/sec) or more.

(2-2) Raw material

[0095] The Al-based alloy that is the raw material of the material is, for example, a mother alloy composed of the above-described first composition, or a mother alloy composed of the above-described second composition. Examples of the raw materials of the mother alloy include pure aluminum powder, pure iron powder, an Al-based alloy powder including Al and the first element, an Fe-based alloy powder including at least one of the first element and the second element and Fe, a diamond powder, and the like. Examples of the Al-based alloy powder and the Fe-based alloy powder include alloy powders composed of an alloy including a high concentration of the first element and/or the second element. When such an Al-based alloy powder and/or Fe-based alloy powder is used, it is preferable to add pure aluminum powder or the like so that the content of the first element and the content of the second element are within predetermined ranges.

[0096] Examples of the Al-based alloy include AlNd alloys that include Nd, AlW alloys that include W, and AlSc alloys that include Sc.

[0097] The content of the first element in the Al-based alloy can be, for example, a composition ratio of a eutectic alloy having a melting point of 1000°C or lower, a composition ratio close to the above-described composition ratio, or a composition ratio in which the content of the first element is lower than the composition ratio of a eutectic alloy (balance is Al and unavoidable impurities).

[0098] Examples of Fe-based alloys include NdFe alloys that include Nd (eutectic alloys), NdFeC alloys that include Nd and C (e.g., $NdFe_4C_4$, and the like), NdFeB alloys that include Nd and B, and FeC alloys that include C. The Nd content in the NdFe alloy is, for example, 20 atom% or more and 25 atom% or less (balance is Al and unavoidable impurities). The lower the melting point of the Fe-based alloy, the more preferable it is in terms of production properties and the like.

[0099] The Nd content in the NdFeC alloy is, for example, 10 atom% or more and 15 atom% or less, and the C content

is, for example, 0.5 atom% or more and 1.5 atom% or less (balance is Al and unavoidable impurities).

[0100] The C content in the FeC alloy is, for example, 15 atom% or more and 20 atom% or less (balance is Al and unavoidable impurities).

[0101] The average grain size of the diamond powder is, for example, 5 μm or less.

(2-3) Material shape

[0102] The material is a powdery material or in the form of a thin strip. This is because it is easy to achieve a solidification rate of 1×10^5 °C/sec or more when the powder diameter is small or the thickness is thin. Further, if the material is a powdery material, in the form of a thin strip, or a powder or flakes crushed into short strips, moldability is excellent. Therefore, a dense intermediate material is easily molded.

(2-4) Material size

[0103] The thickness of the thin strips or flakes is, for example, 1 μm or more and 100 μm or less, and may further be 50 μm or less or 40 μm or less. The diameter of an atomized powder is, for example, 5 μm or more and 200 μm or less, and may further be 100 μm or less, or 20 μm or less.

(2-5) Production method of material

[0104] Examples of a method for producing the material in the form of a thin strip include a so-called liquid quenching solidification method. An example of the liquid quenching solidification method is a melt spinning method. Examples of a method for producing the powdery material include an atomizing method. An example of the atomizing method is a gas atomizing method.

[0105] The melt spinning method is a method for producing thin strips and flakes by injecting and quenching a molten metal of the raw material onto a cooling medium such as a roll or a disk that rotates at high speed. Examples of the cooling medium include cooling media made of a metal such as copper. In the melt spinning method, although the solidification rate depends on the Fe content and the like, and the thickness and the like of the thin strips or flakes, the solidification rate is 1.2×10^5 °C/sec or more, and can be further set to 1.5×10^5 °C/sec or more, 5.0×10^5 °C/sec or more, or 1.0×10^6 °C/sec or more. The rotation speed and the like are adjusted so that the solidification speed is 1×10^5 °C/sec or more. In the case of turning the thin strips into flakes, the thin strips are crushed so as to have a length similar to the thickness of the thin strips, for example.

[0106] The atomizing method is a method of producing a powder by letting the molten metal of the raw material flow out from a small hole at the bottom of a crucible, and injecting a gas with a high cooling capacity or water at high pressure to scatter and quench the thin flow of the molten metal. Examples of the above-described gas include argon gas, air, nitrogen, and the like. In the atomizing method, the type of cooling medium (gas type and the like), the molten metal state (injection pressure, flow velocity, and spatial density of molten metal), temperature, and the like are adjusted so that the solidification rate is 1×10^5 °C/sec or more. The spatial density of the molten metal is a relative density with respect to the true density of the Al-based alloy when the molten metal is assumed to be a mixture of the Al-based alloy and the injection gas.

[0107] In addition, the present inventors have obtained the following findings.

[1] A material in which Fe is not substantially precipitated such as that described above has excellent plastic workability, and rolling such as so-called powder rolling can be performed satisfactorily.

[2] The moldability of the rolled material that has been subjected to the rolling is good enough to allow a dense intermediate material to be molded even in cold working.

[0108] From the above findings, the powdery material may be a material obtained by rolling and then crushing a material produced by quenching the above-described molten metal (hereinafter, sometimes referred to as solidified material).

[0109] It is preferable to adjust the rolling conditions of the powder, such as the pressing force and the gap between rolls, so that a rolled material having a predetermined thickness can be obtained. Example of the conditions when using a roll rolling mill including a pair of rolls include the following (a) to (c).

(a) The diameter of each roll is about 50 mm ϕ to 60 mm ϕ.
(b) The pressing force is about 5 tons.
(c) The gap between the rolls is 0 mm.

[0110] The thickness of the rolled material can be appropriately selected. Examples of the thickness include about 0.1 mm or more and 1.5 mm or less, and further about 0.3 mm or more and 1.2 mm or less. If the thickness is in this range, it is easy to produce a rolled material. Further, after rolling, the rolled material is easily crushed, and a powdery material is easily obtained. The size of the crushed powdery material can be appropriately selected within the range in which the intermediate material can be molded. For example, the size of the material is, for example, 50 μm or less.

(2-6) Measurement of solidification rate

[0111] The solidification rate can be adjusted based on the composition of the molten metal, the temperature of the molten metal, the size of the material to be produced (powder diameter, thickness, and the like), and the like. The solidification rate can be measured, for example, by observing the temperature of the molten metal in contact with the mold using a high-sensitivity infrared thermography camera. Examples of the infrared thermography camera include an A6750 (time resolution: 0.0002 sec) manufactured by FLIR Systems. Examples of the mold include, for example in the melt spinning method described later, a copper roll and the like. The solidification rate (°C/sec) is determined by (hot water temperature-300) / t. Here, t (seconds) is the time that elapses during cooling from the hot water temperature (°C) to 300°C. For example, if the hot water temperature is 700°C, the solidification rate is 400/t (°C/sec).

(2-7) Material structure

[0112] The higher the solidification rate, the easier it is to obtain a compound that includes Al and Fe, and particularly a material including almost no coarse compound particle of 1000 nm or more, which is preferable. Here, in structural analysis by X-ray diffraction (XRD), a ratio of the top peak intensity of Al when it is assumed that the total amount of Fe is precipitated and the top peak intensity of the compound (top peak intensity of Al / top peak intensity of the compound) theoretically corresponds to the volume ratio. In the ideal ratio, the difference between the denominator and the numerator is not so large. In contrast, in the above-described material (e.g., solidified material), the denominator (top peak intensity of the compound) is much smaller than the numerator (top peak intensity of Al). Therefore, the above-described ratio is large. For example, the ratio can be 10 times or more, and further 12 times or more, 15 times or more, or 20 times or more, the theoretical ratio. The larger the ratio, the higher the ratio of the solid solution amount to the total amount of Fe, and the lower the ratio of the above-described compound that is present. A material having a high ratio of the solid solution amount has better moldability because coarse compound particles do not act as starting points of cracking. The ratio does not substantially change even if the solidified material is subjected to above-described powder rolling or the like.

(3) Second step: Production of intermediate material

[0113] In this step, the above-described powdery material or flaky material is molded to produce a dense intermediate material. This molding is performed at a temperature at which the compound including Al and Fe does not precipitate, that is, cold or warm. The densification reduces internal voids. As a result, the intermediate material is less likely to crack due to stress concentration in a void portion. In addition, the intermediate material typically has a structure that substantially maintains or is close to the structure of the above-described material. Therefore, the intermediate material has excellent moldability and plastic workability because coarse compound particles and coarse crystal grains are substantially not present. Even when warm working is performed, the amount of the compound particle that precipitates is small, and the compound particle is also very fine.

(3-1) Cold working

[0114] When the above-described material has undergone the above-described powder rolling or the like, the working for molding the intermediate material may be warm working or cold working. In cold working, the compound does not substantially precipitate during molding, and the crystal grains do not substantially grow. Therefore, it is easy to produce an intermediate material that does not substantially include the compound and has a fine crystal structure. Examples of the cold working include press molding using a uniaxial pressing apparatus and the like.

[0115] Examples of the working temperature in cold working include around normal temperature (5°C to 35°C). If the temperature is around normal temperature, precipitation of the compound and crystal growth are suppressed. In addition, the molding does not require thermal energy and the production properties are excellent. If the working temperature is more than normal temperature and less than 250°C, the plastic workability of the material is increased, so that the intermediate material can be easily molded. The working temperature is, for example, 240°C or lower, preferably 200°C or lower, and more preferably 150°C or lower.

[0116] The applied pressure in cold working is preferably selected within a range in which the relative density is 85% or more. The applied pressure is, for example, 0.1 GPa or more and 2.0 GPa or less, preferably 0.5 GPa or more, more

preferably 0.8 GPa or more, and further preferably 1.0 GPa or more. Although the applied pressure depends on the composition, size, and the like of the material, the higher the molding pressure, the higher the relative density tends to be, and the easier it is to obtain a dense intermediate material.

(3-2) Warm working

[0117] When the material has not undergone powder rolling or the like, the working for molding the intermediate material is preferably warm working. This is because the moldability of the material is increased. Examples of warm working include press molding using a uniaxial pressing apparatus or the like, and so-called hot pressing. Further, the warm working may be, for example, warm extrusion.

[0118] The working temperature in warm working is, for example, 300°C or higher and lower than 400°C. When the working temperature is in this range, the moldability of the material is increased, the dense intermediate material can be satisfactorily molded, and precipitation of the compound tends to be suppressed. In addition, excessive growth of the crystal grains of the matrix tends to be suppressed. The lower the working temperature, the more likely it is that precipitation of the compound and crystal growth are suppressed. The higher the working temperature, the higher the plastic workability. From the viewpoint of obtaining good moldability and the like, the working temperature is preferably 320°C or higher and 390°C or lower, and more preferably 380°C or lower. When the working temperature is 375°C or lower, and further 350°C or lower, the compound does not substantially precipitate, and the moldability is better.

[0119] The working temperature is the temperature at which the material is heated (preheating temperature). The heating time is, for example, 1 minute or more and 30 minutes or less. Further, examples of the atmosphere during the heating include an atmospheric atmosphere, a nitrogen atmosphere, a vacuum atmosphere, and the like. An atmospheric atmosphere does not require atmosphere control and is excellent in terms of operation properties.

[0120] The applied pressure in warm working is preferably selected in a range where the relative density is 85% or more. The applied pressure is, for example, 50 MPa or more and 2.0 GPa or less, preferably 100 MPa (0.1 GPa) or more, and more preferably 700 MPa or more. When the applied pressure is 1.0 GPa or more, and further 1.5 GPa or more, the intermediate material tends to be denser.

(3-3) Relative density

[0121] If the relative density of the intermediate material is 85% or more, hot working and the like can be easily performed in the next step. Further, the relative density of the molded body produced in the next step can be set to 85% or more. That is, a dense Al alloy material is produced. As described above, a dense Al alloy material has excellent strength and hardness at room temperature as well as heat resistance. From the viewpoint of obtaining good moldability, higher density, and the like, the relative density of the intermediate material is preferably 90% or more, more preferably 92% or more, further preferably 93% or more, and still further preferably 95% or more. When warm extrusion is performed, an intermediate material (extruded material) having a higher relative density can be produced. The relative density of the extruded material depends on the material before extrusion, the extrusion conditions, or the like, but is, for example, 98% or more, preferably 99% or more, and may be substantially 100%.

(3-4) Other molding methods

[0122] In addition to the above-described hot pressing and extrusion, the powdery material can be stored in a metal tube, and extruded from the metal tube having both ends sealed. Examples of the metal tube include tubes made of pure aluminum or an aluminum alloy, pure copper, a copper alloy, or the like. Examples of pure aluminum include JIS standard, alloy number A1070, and the like. Examples of aluminum alloys include JIS standard, alloy numbers A5056 and A6063, and the like. After extrusion, based on the metal tube, the surface layer may be removed or kept. When the surface layer is to be kept, a coated Al alloy material having the surface layer as a coating layer, for example, a copper-coated Al alloy material or the like, is produced. The size of the metal tube is preferably selected according to the filling amount of the material, the size of the material, the thickness of the coating layer in the case of a coating layer, and the like.

[0123] The intermediate material may optionally be cut or the like after molding.

(4) Third step: Precipitation

[0124] In this step, the intermediate material is further molded to produce an Al alloy material having a predetermined shape. This molding is performed at a temperature at which the compound that includes Al and Fe can be precipitated, for example, is hot molding. The intermediate material not only has excellent moldability and plastic workability, but can be subjected to hot working, and therefore an Al alloy material having a predetermined shape can be satisfactorily molded. Further, since molding and precipitation are one step, the number of steps is low. In this respect, this production

method has better production properties of Al alloy material.

[0125] The working temperature is, for example, 400°C or higher and 500°C or lower. If the working temperature is in this range, the Al alloy material can be satisfactorily molded. Further, when the working temperature is in this range, the compound can be appropriately precipitated, and the compound and the crystal grains of the matrix can be suppressed from excessive growth. The lower the working temperature, the more growth of the compound and the crystals tends to be suppressed. The higher the working temperature, the higher the moldability. From the viewpoint of obtaining good moldability and suppressing the growth of the compound and the crystals, and the like, the working temperature is preferably 480°C or lower, and more preferably 450°C or lower.

[0126] The working temperature is the temperature at which the material is heated (preheating temperature). The heating time is, for example, 1 minute or more and 30 minutes or less. Further, the atmosphere during the heating may be the same as the atmospheres described above for the conditions of warm working.

[0127] Examples of hot working include hot forging and hot extrusion.

(5) Other steps

[0128] After the third step, cutting and the like can optionally be performed.

[0129] Instead of the third step described above, a step of heat-treating the intermediate material can be carried out. In this step, the intermediate material is heated to a temperature at which the compound that includes Al and Fe can be precipitated to cause the above-described compound to precipitate. Depending on the shape and size of the intermediate material, it may be possible to obtain the final product by only a heat treatment without performing the above-described working such as hot forging or hot extrusion.

[0130] This heat treatment may be a batch treatment or a continuous treatment. A batch treatment is a treatment in which the target of the heat treatment is sealed in a heating vessel such as an atmosphere furnace and heated. A continuous treatment is a treatment in which the target of the heat treatment is continuously supplied to a heating vessel such as a belt furnace and heated.

[0131] In the case of a batch treatment, the heat treatment temperature is, for example, more than 400°C and 500°C or lower, and preferably 420°C or higher. Examples of the holding time include about 10 seconds or more and 6 hours or less. The holding time is preferably 0.1 hour or more and 4 hours or less, more preferably 1 hour or more and 3 hours or less, further preferably 2 hours or less, and still further preferably 1.5 hours or less. As the atmosphere during the heat treatment, refer to the atmospheres described above for the conditions of the warm working. In the continuous treatment, parameters such as belt speed may be adjusted so that the tensile strength, Vickers hardness, elongation at break, and the like after heat treatment satisfy the predetermined ranges described above.

<Test Example 1>

[0132] Al alloy materials having various compositions were produced under various conditions, and the mechanical properties at room temperature, heat resistance, and structure of the obtained Al alloy materials were examined.

(1) Explanation of the tables

[0133] The composition and production conditions are shown in the odd-numbered tables among the following Tables 1 to 20. The even-numbered tables among Tables 1 to 20 show the mechanical properties and the like.

Tables 1 to 6 show samples that include Fe and Nd, but have different production conditions.
Tables 7 and 8 show samples that include Fe and W.
Tables 9 and 10 show samples that include Fe and Sc.
Tables 11 and 12 show samples that include Fe, Nd, and C.
Tables 13 and 14 show samples that include Fe, Nd, and B.
Tables 15 and 16 show samples that include Fe, W, and C.
Tables 17 and 18 show samples that include Fe, W, and B.
Tables 19 and 20 show samples that include Fe, Sc, and C.
Tables 21 and 22 show samples that include Fe, Sc, and B.

[0134] Hereinafter, Nd, W, and Sc may be referred to as the first element, and C and B may be referred to as the second element.

(2) Sample production

(2-1) Sample production using liquid quenching solidification method

[0135] The Al alloy materials of Samples No. 1 to No. 50 and No. 76 to No. 159 shown in Tables 1 to 4 and Tables 7 to 22 were produced as follows.

(2-1-1) Production of material

[0136] Molten metals of Al-based alloys composed of the first elements shown in the odd-numbered tables and Fe, with the balance being Al and unavoidable impurities, were produced. Further, molten metals of Al-based alloys that include the first elements and the second elements shown in the odd-numbered tables and Fe, with the balance being Al and unavoidable impurities, were produced. The content (atom%) of each of the Fe, first element, and second element shown in the odd-numbered tables is the atomic ratios when the Al-based alloy is 100 atom%. The Al-based alloys (mother alloys) used for the molten metals were produced by using the above-described pure aluminum powder, pure iron powder, Al-based alloy powder, Fe-based alloy powder, diamond powder, and the like as raw materials. When necessary, the mother alloys were subjected to a solution treatment. The amount of the above-described added raw materials was adjusted so that the content was as shown in the odd-numbered tables.

[0137] Using the molten metal, a thin strip was produced by a liquid quenching solidification method, in the case here, by a melt spinning method under the following conditions. The obtained thin strip was crushed into a powder.

[0138] In a reduced-pressure argon atmosphere (-0.02 MPa), the temperature was raised to 1000°C to dissolve the mother alloy and produce a molten metal. The molten metal was injected onto a copper roll rotating at a peripheral speed of 50 m/s or 10 m/s to produce a thin strip. The peripheral speed (meters / second) of the roll is shown in the odd-numbered tables. Further, the solidification rate (°C/sec) of the molten metal is shown in the odd-numbered tables. Here, the solidification rate was 1.5×10^5 °C/sec or 7.5×10^6 °C/sec. The width of the thin strip was about 2 mm. The thickness of the thin strip was about 30 μm. The length of the thin strip was indefinite.

[0139] When the structure of the obtained strip of each sample was analyzed by XRD, a peak of a compound that includes Al and Fe (e.g., $Al_{13}Fe_4$) was observed. However, the ratio (top peak intensity of Al / top peak intensity of the compound) was 10 times or more the above-described theoretical ratio. Moreover, when a cross section of the thin strip of each sample was observed with a scanning electron microscope (SEM), no compound described above having a size of 1000 nm or more was observed. The observation magnification here was 10,000 times. From these facts, it can be said that the thin strip of each sample substantially does not include a coarse compound particle.

(2-1-2) Production of intermediate material

[0140] The intermediate material was molded using a powder obtained by crushing the above-described thin strip. Here, after the powder was dried to remove moisture adsorbed on the surface of the powder, a first molded body having a relative density of 85% or more was produced by cold working. Next, the first molded body was preheated, and a second molded body having a relative density of 90% or more was produced by warm working. The second molded body is the intermediate material. The intermediate material was a cylinder having a diameter of 40 mm and a length of 50 mm.

[0141] The molding of the first molded body was cold press molding in which the following preheating was performed. The applied pressure was 0.1 GPa. The preheating conditions were an argon atmosphere, a working temperature of 200°C, and a holding time of 120 minutes.

[0142] The molding of the second molded body was warm press molding in which the following preheating was performed. The applied pressure was 1.5 GPa. The preheating conditions were an atmospheric atmosphere, a working temperature of 350°C, and a holding time of 30 minutes.

(2-1-3) Precipitation step

[0143] The intermediate material of each obtained sample was subjected to hot working. The hot working here was hot extrusion in which the following preheating was performed. The preheating conditions were an atmospheric atmosphere, a working temperature of 400°C, and a holding time of 10 minutes. As a result of this hot working, an Al alloy material composed of Al-based alloy having the composition shown in the odd-numbered tables was obtained. The produced Al alloy material was a cylinder having a diameter of 10 mm and a length of about 1000 mm.

(2-2) Sample utilizing gas atomization method

[0144] The Al alloy materials of Samples No. 51 to No. 71 shown in Tables 5 and 6 were produced as follows.

[0145] In the same manner as for the above-described Sample No. 1 and the like, a molten metal of an Al-based alloy that includes Fe and Nd with the balance being Al and unavoidable impurities was produced. Using this molten metal, an atomized powder was produced by a gas atomizing method. Here, known conditions were used. The solidification rate of the molten metal was 1.0×10^4 °C/sec. The average grain size of the atomized powder was about 100 μm.

[0146] Using the atomized powder, cold working, warm working, and hot working were performed in that order under the same conditions as for the above-described Sample No. 1 and the like to obtain an Al alloy material composed of an Al-based alloy having the composition shown in Table 5. The produced Al alloy material was a cylinder having a diameter of 10 mm and a length of about 1000 mm.

(3) Mechanical properties

[0147] The Vickers hardness (Hv), tensile strength (MPa), and elongation at break (%) were measured for the Al alloy material of each of the obtained samples. The results are shown in the even-numbered tables.

[0148] The Vickers hardness (Hv) was measured in accordance with JIS Z 2244 (Vickers hardness test - Test method, 2009). The test force was 0.4903 N. The Vickers hardness (Hv) at 25°C and the Vickers hardness (Hv) at 250°C were each measured. In the tables, "<20" means that the Vickers hardness was less than 20.

[0149] The tensile strength (MPa) and the elongation at break (%) were measured in accordance with JIS Z 2241 (Metallic material tensile test method, 1998). The tensile strength and the elongation at break at 25°C and the tensile strength at 250°C were each measured.

[0150] For the measurement, a commercially available measuring device capable of measuring the Vickers hardness at 25°C and 250°C and a tensile test can be used.

(4) Heat resistance

[0151] The rate of decrease K_{TS} (%/°C) in the tensile strength of the Al alloy material of each sample from 25°C to 250°C was determined. The results are shown in the even-numbered tables. The rate of decrease K_{TS} was determined by $[(T_r\text{-}T_h) / \{(250\text{-}25) \times T_r\}] \times 100$. T_r is the tensile strength at 25°C, and Th is the tensile strength at 250°C.

[0152] The temperature coefficient K_{Hv} (%/°C) relating to the decrease in Vickers hardness of the Al alloy material of each sample from 25°C to 250°C was determined. The results are shown in the even-numbered tables. The temperature coefficient K_{Hv} was determined from $[(H_r\text{-}H_h) / \{(250\text{-}25) \times H_r\}] \times 100$. H_r is the Vickers hardness (H_v) at 25°C, and H_h is the Vickers hardness at 250°C. Regarding samples with a "-" in the tables, a temperature coefficient K_{Hv} was not determined because the Vickers hardness H_h at 250°C was too low (here, less than 20).

(5) Relative density

[0153] The relative density (%) of the Al alloy material of each obtained sample was determined. The results are shown in the even-numbered tables. The relative density was determined from (apparent density / true density) × 100 using the apparent density of the Al alloy material and the true density of the Al alloy material. The true density was determined using the composition of the Al alloy material and the density of the added element(s). The composition of the Al alloy material may be determined by component analysis. The apparent density was determined by measuring the mass and volume of the Al alloy material and calculating (mass / volume).

(6) Structure observation

[0154] An arbitrary cross section of the Al alloy material of each obtained sample was taken, and the cross section was observed by SEM. In all the samples, the matrix had a crystal structure. Further, in all the samples, a compound that includes Al and Fe (here, a compound in which the atomic ratio of Fe to Al was 0.1 or more (10 atom%), for example, $Al_{13}Fe_4$) was present in the matrix. The compound was mainly a precipitate. In the specific sample groups I and II described later, a particle composed of the compound were dispersed in the matrix.

[0155] In the cross section, the average grain size (nm) of the crystal grains forming the matrix, the average length (nm) of the particle (compound particle) composed of the compound described above, the aspect ratio of the compound particle, and the average number of the compound particles per unit area (number / (500 nm × 500 nm)) were examined. The results are shown in the even-numbered tables.

[0156] The average grain size (nm) of the crystal grains of the matrix was determined as follows.

[0157] A cross section of the Al alloy material was observed by SEM. From the SEM image of this cross section, a

measurement region (field of view) of 10 μm × 10 μm was taken. A total of 30 or more measurement regions was taken from one cross section or a plurality of cross sections. All the crystal grains present in each measurement region were extracted. A circle having an area equivalent to the cross-sectional area of each crystal grain was obtained. The diameter of this circle (equivalent area circle) was defined as the grain size of the crystal grains. Crystal grains having a grain size of 50 nm or more were extracted. That is, the crystal grains having a grain size of less than 50 nm were not used for calculating the average grain size. The grain size of the extracted crystal grains was averaged. The obtained average value was taken as the average grain size. This average grain size is shown in the even-numbered tables. The observation magnification here was 10,000 times. With a resolution at this magnification, it is very difficult to clearly measure crystals of less than 10 nm and a compound particle, which is described later, of less than 10 nm. Therefore, here, crystals having a diameter of 50 nm or more are used for calculating the average grain size.

[0158] The extraction of the crystal grains and the extraction of the compound particle, which is described later, can be easily performed by image processing the SEM image using commercially available image processing software. A metallurgical microscope can also be used to observe the cross sections. The magnification of the microscope is, as described above, or as described below, adjusted within a clearly measurable range of the size of the object to be measured. Further, when observing the cross sections, it is effective to perform grain boundary etching by an appropriate solution treatment and to obtain an SEM image having crystal orientation information by EBSD (electron backscatter diffraction method).

[0159] The average length (nm) of the compound particle was calculated as follows.

[0160] A cross section of the Al alloy material was observed by SEM. From the SEM image of this cross section, a measurement region of 10 μm × 10 μm was taken. A total of 30 or more measurement regions was taken from one cross section or a plurality of cross sections. All the compound particles precipitated in each measurement region were extracted. The maximum length of each compound particle was measured. Here, the observation magnification was set to 10,000 times, and the compound particles having a maximum length of 10 nm or more were extracted. That is, compound particles having a maximum length of less than 10 nm were not used in the calculation of the average length. The maximum length of the extracted compound particles was averaged. The calculated average value was taken as the average length. This average length is shown in the even numbered tables.

[0161] The aspect ratio of the compound particle was calculated as follows.

[0162] The aspect ratio was taken as the ratio of the major axis length to the minor axis length of the compound particle, that is, (major axis length / minor axis length). The major axis length (nm) was taken as the maximum length of the compound particle. The minor axis length (nm) was taken as the maximum value among the lengths of the line segments in the direction orthogonal to the major axis direction. Here, as described above, the aspect ratio was determined for the compound particles having a maximum length of 10 nm or more. The aspect ratio of each of these compound particles was averaged. The obtained average value was taken as the aspect ratio. This aspect ratio is shown in the even numbered tables.

[0163] The average number (particles) of the compound particle was calculated as follows.

[0164] A cross section of the Al alloy material was observed by SEM. From the SEM image of this cross section, a measurement region (field of view) of 500 nm × 500 nm was taken. A total of 30 or more measurement regions were taken from one cross section or a plurality of cross sections. The number of the compound particle present in each measurement region and having a maximum length of 10 nm or more was measured. The number of the compound particle in 30 or more measurement regions was totaled, and the total number was divided by the number of measurement regions (30 or more) and averaged. The obtained average value was taken as the average number of the compound particles present per unit area. This average number is shown in the even-numbered tables. The observation magnification here was 30,000 times. In the tables, "<5" means that the compound particle was too large to fit within the above-described measurement region and could not be counted.

(7) Component analysis

[0165] In addition, the structure of the compound (e.g., $Al_{13}Fe_4$) can be examined by performing structural analysis by XRD on a cross section of the Al alloy material. Since surface oxides and the like have a large influence, this analysis can be accurately performed after sufficiently removing surface oxides and the like, or by evaluating the inside of the sample by transmissive XRD or the like using radiated light. Further, by identifying the elements constituting the compound, it can be confirmed that, for example, Nd is included in the compound that includes Fe and Al. By identifying the elements constituting the matrix, the Al content in the matrix can be examined. This identification can be carried out by using an apparatus capable of local component analysis, such as a transmission electron microscope (TEM) attached to a measuring apparatus by energy dispersive X-ray spectroscopy (EDX). In the specific sample groups I and II described later, the Al content in the matrix is 99 atom% or more.

[Table 1]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Nd content (atom%)
1	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.0	0.000
2	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.0	0.006
3	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.0	0.020
4	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.0	0.100
5	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.0	0.150
6	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.4	0.000
7	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.4	0.006
8	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.4	0.020
9	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.4	0.100
10	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	1.4	0.150
11	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	3.6	0.000
12	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	3.6	0.006
13	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	3.6	0.020
14	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	3.6	0.100
15	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	3.6	0.150
16	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	6.2	0.000
17	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	6.2	0.006
18	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	6.2	0.020
19	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	6.2	0.100
20	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	6.2	0.150
21	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	7.0	0.000

(continued)

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Nd content (atom%)
22	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^{6}	7.0	0.006
23	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^{6}	7.0	0.020
24	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^{6}	7.0	0.100
25	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^{6}	7.0	0.150

[Table 2]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
1	99%	860	140	3.7	<5	83	260	21.1	<20	-	50	0.36
2	99%	850	68	2.4	5	88	280	17.2	<20	-	80	0.32
3	99%	830	60	2.4	6	93	290	16.8	24	0.33	75	0.33
4	99%	820	51	2.3	8	103	320	15.3	29	0.32	90	0.32
5	98%	780	43	2.0	14	112	340	14.0	32	0.32	95	0.32
6	98%	600	143	3.8	<5	96	290	13.5	<20	-	40	0.38
7	98%	590	33	2.5	26	104	385	9.4	38	0.28	150	0.27
8	98%	570	27	2.5	38	116	390	8.3	48	0.26	155	0.27
9	98%	560	25	2.5	45	123	420	4.7	54	0.25	175	0.26
10	98%	540	15	1.7	181	130	335	2.8	57	0.25	145	0.25
11	98%	580	153	5.0	<5	113	355	12.0	27	0.34	90	0.33
12	98%	580	32	2.6	69	120	405	8.7	44	0.28	170	0.26
13	98%	560	27	2.5	100	125	410	7.8	49	0.27	170	0.26
14	98%	550	23	2.5	134	137	430	4.2	57	0.26	180	0.26
15	97%	520	17	2.1	298	139	320	2.5	64	0.24	140	0.25
16	96%	540	169	6.3	<5	117	385	9.5	30	0.33	90	0.34
17	96%	540	30	2.9	118	120	460	6.8	47	0.27	190	0.26
18	96%	530	26	2.7	170	127	475	6.3	50	0.27	210	0.25
19	96%	520	24	2.5	216	141	470	3.1	62	0.25	205	0.25
20	95%	470	20	2.2	355	153	290	1.3	70	0.24	140	0.23
21	96%	490	204	7.8	<5	92	260	2.7	24	0.33	75	0.32

(continued)

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
22	96%	480	103	5.1	6	107	310	2.9	47	0.25	145	0.24
23	96%	480	92	4.8	8	112	295	2.0	52	0.24	140	0.23
24	95%	460	88	4.7	9	116	265	1.4	53	0.24	135	0.22
25	95%	430	83	3.9	11	127	250	0.7	61	0.23	140	0.20

[Table 3]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Nd content (atom%)
26	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.000
27	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.006
28	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.020
29	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.100
30	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.150
31	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.000
32	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.006
33	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.020
34	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.100
35	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.150
36	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.000
37	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006
38	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.020
39	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100
40	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.150
41	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.000
42	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.006
43	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.020
44	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.100
45	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.150
46	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.000

(continued)

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Nd content (atom%)
47	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.006
48	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.020
49	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.100
50	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.150

[Table 4]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
26	100%	2,200	330	4.8	<5	73	225	18.5	<20	-	40	0.37
27	99%	1,880	61	3.6	<5	84	260	13.5	20	0.34	60	0.34
28	99%	1,830	58	3.4	<5	86	265	13.1	22	0.33	60	0.34
29	99%	1,720	68	3.4	<5	91	280	10.7	23	0.33	80	0.32
30	99%	1,610	54	3.1	6	93	290	8.4	26	0.32	95	0.30
31	99%	2,130	360	4.9	<5	68	210	23.4	<20	-	50	0.34
32	99%	1,680	53	2.6	10	86	310	18.3	33	0.27	135	0.25
33	99%	1,560	50	2.6	11	89	320	8.9	37	0.26	140	0.25
34	99%	1,340	46	2.5	12	96	330	7.8	42	0.25	145	0.25
35	99%	1,180	43	2.2	15	110	250	2.9	46	0.26	95	0.28
36	99%	2,090	420	6.5	<5	65	200	13.6	<20	-	50	0.33
37	99%	1,440	48	2.6	30	93	310	11.5	37	0.27	135	0.25
38	98%	1,390	44	2.5	37	98	325	8.2	43	0.25	135	0.26
39	98%	1,250	42	2.5	40	105	345	4.9	46	0.25	145	0.26
40	98%	1,020	38	2.1	59	115	245	1.7	50	0.25	90	0.28
41	99%	2,020	440	8.2	<5	70	215	12.0	<20	-	50	0.34
42	99%	1,410	51	2.5	48	106	330	10.5	39	0.28	150	0.24
43	99%	1,350	48	3.5	38	120	370	7.2	44	0.28	160	0.25
44	99%	1,200	45	3.3	42	134	375	3.5	50	0.28	175	0.24
45	99%	960	39	2.9	69	136	230	1.1	60	0.25	95	0.26
46	99%	1,880	480	11.7	<5	73	225	3.8	<20	-	65	0.32

(continued)

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
47	99%	1,370	84	7.8	6	90	265	2.6	33	0.28	90	0.29
48	98%	1,300	79	7.5	7	101	260	2.4	40	0.27	95	0.28
49	98%	1,080	74	7.5	7	115	230	1.2	45	0.27	85	0.28
50	98%	850	72	7.4	8	118	175	0.5	49	0.26	70	0.27

[Table 5]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Nd content (atom%)
51	gas atomization method	1.0×10^4	1.0	0.000
52	gas atomization method	1.0×10^4	1.0	0.006
53	gas atomization method	1.0×10^4	1.0	0.020
54	gas atomization method	1.0×10^4	1.0	0.100
55	gas atomization method	1.0×10^4	1.0	0.150
56	gas atomization method	1.0×10^4	1.4	0.000
57	gas atomization method	1.0×10^4	1.4	0.006
58	gas atomization method	1.0×10^4	1.4	0.020
59	gas atomization method	1.0×10^4	1.4	0.100
60	gas atomization method	1.0×10^4	1.4	0.150
61	gas atomization method	1.0×10^4	3.6	0.000
62	gas atomization method	1.0×10^4	3.6	0.006
63	gas atomization method	1.0×10^4	3.6	0.020
64	gas atomization method	1.0×10^4	3.6	0.100
65	gas atomization method	1.0×10^4	3.6	0.150
66	gas atomization method	1.0×10^4	6.2	0.000
67	gas atomization method	1.0×10^4	6.2	0.006
68	gas atomization method	1.0×10^4	6.2	0.020
69	gas atomization method	1.0×10^4	6.2	0.100
70	gas atomization method	1.0×10^4	6.2	0.150
71	gas atomization method	1.0×10^4	7.0	0.000
72	gas atomization method	1.0×10^4	7.0	0.006
73	gas atomization method	1.0×10^4	7.0	0.020
74	gas atomization method	1.0×10^4	7.0	0.100
75	gas atomization method	1.0×10^4	7.0	0.150

[Table 6]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
51	100%	3,630	1,340	8.7	<5	52	130	4.3	<20	-	30	0.34
52	100%	3,550	210	3.7	<5	63	140	2.9	<20	-	35	0.33
53	100%	3,540	200	3.6	<5	65	140	2.7	<20	-	35	0.33
54	99%	3,480	165	3.5	<5	70	145	2.7	<20	-	40	0.32
55	99%	3,460	155	3.3	<5	72	150	2.6	<20	-	45	0.31
56	100%	3,400	1,520	9.4	<5	50	140	4.2	<20	-	30	0.35
57	100%	3,320	250	3.8	<5	58	135	2.4	<20	-	50	0.28
58	100%	3,290	230	3.6	<5	63	145	2.5	<20	-	55	0.28
59	100%	3,280	215	3.5	<5	68	150	2.2	22	0.30	60	0.27
60	99%	3,250	180	3.2	<5	73	120	1.3	31	0.26	50	0.26
61	99%	3,420	1,670	11.1	<5	50	105	4.3	<20	-	30	0.32
62	99%	3,390	240	3.9	<5	60	125	2.6	<20	-	50	0.27
63	98%	3,330	210	3.8	<5	66	135	2.3	20	0.31	55	0.26
64	97%	3,250	190	3.5	<5	72	115	2.0	23	0.30	45	0.27
65	97%	3,070	150	3.3	<5	77	110	0.9	28	0.28	45	0.26
66	99%	3,310	1,580	13.5	<5	53	110	4.4	<20	-	25	0.34
67	98%	3,240	260	5.3	<5	57	110	1.7	24	0.26	45	0.26
68	97%	3,140	230	5.1	<5	57	115	1.6	25	0.25	50	0.25
69	97%	3,050	220	5.2	<5	59	110	1.6	26	0.25	45	0.26
70	97%	2,900	230	5.2	<5	62	95	0.8	28	0.24	45	0.23
71	99%	3,330	1,650	15.2	<5	48	101	3.8	<20	-	20	0.36

(continued)

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
72	97%	3,220	320	6.6	<5	56	118	1.2	25	0.25	25	0.35
73	97%	3,100	310	6.3	<5	58	122	1.1	27	0.24	50	0.26
74	96%	2,920	295	6.3	<5	59	124	0.7	27	0.24	50	0.27
75	96%	2,840	270	6.1	<5	60	126	0.6	30	0.22	60	0.23

[Table 7]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	W content (atom%)
76	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.006
77	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.020
78	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.100
79	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.150
80	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.006
81	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.020
82	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.100
83	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.150
84	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006
85	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.020
86	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100
87	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.150
88	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.006
89	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.020
90	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.100
91	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.150
92	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.006
93	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.020
94	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.100
95	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.150

[Table 8]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
76	99%	1,940	66	3.3	<5	96	285	10.9	25	0.33	80	0.32
77	99%	1,900	60	3.1	<5	98	300	10.3	28	0.32	80	0.33
78	99%	1,870	75	3.0	<5	105	320	8.6	30	0.32	95	0.31
79	98%	2,050	60	2.8	5	108	325	6.7	33	0.31	95	0.31
80	99%	1,680	53	2.4	10	100	285	14.3	41	0.26	135	0.23
81	99%	1,660	52	2.3	11	103	315	7.0	45	0.25	145	0.24
82	98%	1,500	50	2.3	12	115	350	6.3	53	0.24	160	0.24
83	98%	1,460	47	2.1	15	128	230	2.6	56	0.25	90	0.27
84	99%	1,620	53	2.4	27	104	310	9.6	43	0.26	145	0.24
85	98%	1,520	49	2.3	32	111	330	6.6	51	0.24	150	0.24
86	97%	1,380	47	2.3	36	121	330	3.5	56	0.24	150	0.24
87	97%	1,310	38	2.0	63	128	240	1.2	58	0.24	95	0.27
88	98%	1,430	56	2.3	43	118	355	6.8	46	0.27	175	0.23
89	98%	1,410	51	3.3	36	134	380	5.3	53	0.27	180	0.23
90	97%	1,430	49	3.1	42	146	400	3.0	58	0.27	200	0.22
91	96%	1,370	44	2.5	65	149	225	0.8	69	0.24	85	0.28
92	98%	1,620	104	7.3	4	101	245	2.0	40	0.27	90	0.28
93	97%	1,530	97	6.5	5	115	250	1.7	48	0.26	90	0.28
94	97%	1,420	88	6.4	6	131	210	0.8	54	0.26	90	0.25
95	96%	1,290	81	6.7	6	135	160	0.5	59	0.25	70	0.25

[Table 9]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Sc content (atom%)
96	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.006
97	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.020
98	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.100
99	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.0	0.150
100	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.006
101	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.020
102	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.100
103	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	1.4	0.150
104	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006
105	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.020
106	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100
107	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.150
108	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.006
109	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.020
110	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.100
111	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.150
112	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.006
113	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.020
114	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.100
115	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	7.0	0.150

[Table 10]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
96	100%	1,750	59	3.3	<5	86	265	13.6	22	0.33	65	0.34
97	100%	1,680	53	3.1	<5	88	275	12.9	25	0.32	65	0.34
98	100%	1,660	67	3.0	<5	95	290	10.4	27	0.32	80	0.32
99	99%	1,720	50	2.8	7	99	295	8.3	30	0.31	85	0.32
100	99%	1,580	48	2.5	12	90	260	18.3	37	0.26	125	0.23
101	99%	1,510	46	2.5	13	94	270	9.1	41	0.25	140	0.21
102	99%	1,350	45	2.4	13	105	320	8.1	49	0.24	150	0.24
103	98%	1,300	43	2.3	14	116	225	3.3	50	0.25	80	0.29
104	99%	1,480	48	2.6	28	94	280	12.7	38	0.26	140	0.22
105	99%	1,400	43	2.5	35	103	300	8.9	48	0.24	140	0.24
106	98%	1,250	41	2.3	45	110	320	4.5	53	0.23	140	0.25
107	98%	1,190	36	2.0	67	117	240	1.8	55	0.24	85	0.29
108	98%	1,300	51	2.6	46	102	325	8.4	47	0.24	165	0.22
109	98%	1,280	45	3.3	46	121	345	6.6	53	0.25	170	0.23
110	98%	1,280	44	3.0	55	127	375	3.6	58	0.24	185	0.23
111	98%	1,240	39	2.8	78	130	240	1.0	71	0.20	75	0.31
112	98%	1,460	90	7.2	5	88	250	2.8	40	0.24	80	0.30
113	98%	1,350	85	6.1	6	101	255	2.4	48	0.23	80	0.31
114	98%	1,300	77	5.8	8	117	230	1.1	55	0.24	80	0.29
115	97%	1,150	68	6.3	10	123	170	0.6	58	0.23	65	0.27

[Table 11]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Nd content (atom%)	C content (atom%)
116	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	0.01
117	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	0.1
118	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	3.6	0.006	0.1
119	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	1
120	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	2
121	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	0.01
122	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	0.1
123	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	3.6	0.100	0.1
124	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	1
125	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	2
126	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	6.2	0.100	1
127	liquid quenching solidification method (roll peripheral speed: 50 m/s)	7.5×10^6	6.2	0.100	1

[Table 12]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
116	100%	1,230	59	1.9	40	93	280	24.3	43	0.24	130	0.24
117	100%	1,280	40	1.8	63	98	295	20.0	47	0.23	140	0.23
118	100%	420	22	1.8	208	127	420	14.6	63	0.22	195	0.24
119	99%	1,240	38	1.8	70	112	340	8.7	55	0.23	165	0.23
120	96%	1,150	35	2.4	66	134	250	2.2	70	0.21	85	0.29
121	100%	980	44	1.8	48	105	320	13.8	51	0.23	155	0.23
122	99%	950	42	1.8	52	118	355	12.4	58	0.23	175	0.23
123	100%	360	19	1.7	293	148	460	8.8	72	0.23	220	0.23
124	99%	930	36	1.7	82	124	370	5.3	62	0.22	185	0.22
125	96%	900	33	2.2	75	146	275	1.8	79	0.20	95	0.29
126	99%	890	32	1.7	182	145	435	7.3	73	0.22	200	0.24
127	96%	320	18	1.8	530	161	480	6.1	91	0.19	255	0.21

[Table 13]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Nd content (atom%)	B content (atom%)
128	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	0.01
129	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	0.1
130	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	1
131	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	2
132	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	0.01
133	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	0.1
134	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	1
135	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	2

[Table 14]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
128	99%	1,100	33	1.8	88	104	320	21.3	56	0.21	160	0.22
129	99%	1,050	31	1.7	106	108	330	16.5	60	0.20	175	0.21
130	99%	1,020	30	1.6	119	120	345	6.0	67	0.20	180	0.21
131	96%	1,180	34	1.8	83	152	220	0.6	88	0.19	85	0.27
132	99%	930	38	1.7	74	123	350	10.1	63	0.22	180	0.22
133	98%	910	36	1.6	84	130	355	8.4	68	0.21	190	0.21
134	98%	880	32	1.5	117	139	370	5.2	74	0.21	200	0.20
135	96%	950	31	1.7	110	165	275	0.4	92	0.20	90	0.30

[Table 15]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	W content (atom%)	C content (atom%)
136	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	0.01
137	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	1
138	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	2
139	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	0.01
140	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	1
141	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	2

[Table 16]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
136	98%	1,390	40	1.7	66	100	295	12.6	46	0.24	135	0.24
137	98%	1,310	38	1.7	74	116	345	6.4	53	0.24	170	0.23
138	95%	1,240	34	1.6	98	144	245	0.7	73	0.22	95	0.27
139	98%	1,080	44	1.6	59	113	340	8.7	55	0.23	175	0.22
140	97%	1,020	40	1.5	75	128	365	5.0	63	0.23	185	0.22
141	95%	1,010	37	1.5	88	152	220	0.8	80	0.21	85	0.27

[Table 17]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	W content (atom%)	B content (atom%)
142	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	0.01
143	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	1
144	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	2
145	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	0.01
146	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	1
147	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	2

[Table 18]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
142	98%	960	29	1.6	134	110	335	14.3	61	0.20	180	0.21
143	97%	930	25	1.6	180	124	350	7.1	71	0.19	190	0.20
144	95%	800	30	1.7	118	167	210	0.7	93	0.20	75	0.29
145	98%	930	34	1.5	104	128	360	8.6	68	0.21	200	0.20
146	97%	920	27	1.5	165	150	385	5.5	83	0.20	200	0.21
147	94%	890	33	1.6	100	178	195	0.6	102	0.19	80	0.26

[Table 19]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Sc content (atom%)	C content (atom%)
148	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	0.01
149	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	1
150	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	2
151	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	0.01
152	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	1
153	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	2

[Table 20]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
148	99%	1,500	36	1.9	77	93	270	17.3	41	0.25	125	0.24
149	99%	1,420	34	1.8	84	103	295	6.6	49	0.23	135	0.24
150	97%	1,340	33	1.8	94	129	265	1.0	58	0.24	105	0.27
151	99%	1,300	41	1.8	55	97	300	10.5	47	0.23	145	0.23
152	98%	1,250	37	1.8	71	121	365	5.2	55	0.24	150	0.26
153	96%	1,180	35	1.7	80	141	240	0.5	68	0.23	75	0.31

[Table 21]

Sample No.	Casting method	Solidification rate (°C/sec)	Fe content (atom%)	Sc content (atom%)	B content (atom%)
154	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	0.01
155	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	1
156	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.006	2
157	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	0.01
158	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	1
159	liquid quenching solidification method (roll peripheral speed: 10 m/s)	1.5×10^5	3.6	0.100	2

[Table 22]

Sample No.	Density of molded body (relative density)	Structure				25°C (room temperature)			250°C			
		Average grain size of crystal grain (nm)	Average length of compound particle (nm)	Aspect ratio of compound particle	Average number of compound particle per unit area	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation at break (%)	Vickers hardness (Hv)	Temperature coefficient of Vickers hardness (%/°C)	Tensile strength (MPa)	Rate of decrease in tensile strength (%/°C)
154	99%	1,350	30	2.0	99	103	295	13.7	49	0.23	140	0.23
155	99%	1,260	30	1.9	103	124	340	6.7	61	0.23	165	0.23
156	97%	1,220	30	1.9	110	148	280	0.8	75	0.22	95	0.29
157	99%	1,100	32	2.0	82	110	325	9.2	54	0.23	155	0.23
158	98%	1,020	30	1.9	94	130	330	5.0	67	0.22	150	0.24
159	96%	970	31	1.8	94	165	250	1.1	87	0.21	95	0.28

[0166] [a] First, in Tables 1 to 4 and Tables 5 to 6, samples having the same composition are compared with each other.

[0167] Looking at the mechanical properties (Vickers hardness, tensile strength, and elongation at break) at room temperature (25°C in this case), the samples shown in Tables 2 and 4 tend to have higher mechanical properties than the samples shown in Table 6.

[0168] Looking at the properties at a high temperature (250°C in this case), the samples shown in Tables 2 and 4 tend to have a higher Vickers hardness and tensile strength than the samples shown in Table 6.

[0169] Looking at the structure, the samples shown in Tables 2 and 4 tend to have smaller crystal grains than the samples shown in Table 6. Further, the particle composed of the compound that includes Al and Fe tends to be smaller. Furthermore, the number of the compound particles tends to be larger.

[0170] One of the reasons for the differences in mechanical properties is considered to be the difference in solidification rate. The samples shown in Tables 2 and 4 have a high solidification rate. The solidification rate here is 1×10^5 °C/sec or more, and further 1.5×10^5 °C/sec or more (Tables 1 and 3). It is considered that due to the high solidification rate, a fine structure was obtained, as described below. Further, it is considered that the strengthening of the dispersion by the fine compound particle and the strengthening of the grain boundaries by the fine crystal grains were satisfactorily achieved. In addition, it is considered that the occurrence of cracking due to a coarse compound particle could be reduced, and increased brittleness of the alloy at a high temperature was unlikely to occur.

[0171] Although the Fe content is 1.0 atom% or more, the solidification rate is fast, so solidified material is obtained that is a compound particle that includes Al and Fe and does not substantially include a coarse particle. Even in the process of producing an intermediate material using this solidified material, the compound is unlikely to precipitate or grow. By subjecting the intermediate material to hot working, the compound that includes Al and Fe is finely precipitated (see the average length and aspect ratio in Tables 2 and 4). Since the compound particle is fine, the number of the compound particle tends to increase (see the average number in Tables 2 and 4). In addition, the fine compound particle suppresses the growth of crystals, and the crystal grains tend to be finer (see the average grain size in Tables 2 and 4).

[0172] Table 2 and Table 4 are now compared. The samples shown in Table 2 tend to have smaller crystal grains and a smaller compound particle than the samples shown in Table 4. Further, the number of the compound particle tends to be larger. In addition, the samples shown in Table 2 tend to have higher mechanical properties at room temperature than the samples shown in Table 4. Moreover, the tensile strength and Vickers hardness at a high temperature tend to be higher. From these facts, it can be said that the faster the solidification rate, the finer the compound particle and the crystals tend to be. Further, it can be said that the reduction in size of the compound particle and the reduction in size of the crystals contribute to the improvement of the mechanical properties at room temperature and heat resistance.

[0173] In the samples shown in Table 6, the solidification rate is slow. The solidification rate here is 1×10^4 °C/sec (Table 5). When the solidification rate is slow, it is considered that the compound that includes Al and Fe turns into a coarse particle and precipitates in the solidified material, and that the compound is likely to grow more coarsely (needle-shaped) in the subsequent steps. The coarse growth of the compound tends to reduce the number of the compound particle. In addition, a coarse compound particle cannot suppress the growth of the crystals forming the matrix, and the crystal grains of the matrix also tend to grow coarsely. Thus, it is considered that the mechanical properties at room temperature and heat resistance deteriorate because a fine structure is not properly obtained.

[0174] [b] Next, Tables 1 to 4 and Tables 7 to 10 will be looked at. Basically, samples having the same composition are compared.

[0175] Below, Sample No. 7 to No. 19 (excluding No. 10, No. 11, No. 15, and No. 16), No. 32 to No. 44 (excluding No. 35, No. 36, No. 40, and No. 41), No. 80 to No. 90 (excluding No. 83 and No. 87), No. 100 to No. 110 (excluding No. 103 and No. 107) are referred to as a specific sample group I.

[0176] In particular, Sample No. 7 to No. 19 (excluding No. 10, No. 11, No. 15, and No. 16) are referred to as a specific sample group (I-1).

[0177] As shown in the even-numbered tables, it can be seen that the Al alloy materials that include 1.2 atom% or more and 6.5 atom% or less of Fe and 0.005 atom% or more and less than 0.15 atom% of the first element have excellent mechanical properties at room temperature, as well as a high Vickers hardness at a high temperature and a high tensile strength at a high temperature.

[0178] In the specific sample group I, the Vickers hardness at 25°C is 85 Hv or more, and here, further 86 Hv or more. Many samples have a Vickers hardness of 90 Hv or more. In the specific sample group (I-1) having the high solidification rate, the Vickers hardness is 100 Hv or more, and for many samples is 110 Hv or more.

[0179] In the specific sample group I, the tensile strength at 25°C is 250 MPa or more, and here, further 260 MPa or more. Many samples have a tensile strength of 270 MPa or more. In the specific sample group (I-1), the tensile strength is 320 MPa or more, and here, further 350 MPa or more. Many samples have a tensile strength of 400 MPa or more.

[0180] In the specific sample group I, the elongation at break at 25°C is 3% or more. There are many samples in which the extension at break is 3.2% or more, and further 3.5% or more.

[0181] In the specific sample group I, the temperature coefficient of Vickers hardness is 0.30%/°C or less, and here, it is further 0.28/°C or less. For such a specific sample group I, it can be said that Vickers hardness is less likely to

decrease even at 250°C, the Vickers hardness is higher as shown in the even-numbered tables (e.g., 30 Hv or more), and heat resistance is excellent. Since the Vickers hardness at 25°C is as high as 85 Hv or more, it is considered that the Vickers hardness is likely to be high even at 250°C.

[0182] In the specific sample group I, the rate of decrease in tensile strength from 25°C to 250°C is less than 0.28%/°C, and here it is further 0.27%/°C or less. For such a specific sample group I, it can be said that tensile strength is less likely to decrease even at 250°C, and the tensile strength is higher as shown in the even-numbered tables (e.g., 120 MPa or more), and heat resistance is excellent.

[0183] In the specific sample group I, the crystal grains forming the matrix are fine, and the compound particle is also fine. Specifically, the average grain size of the crystal grains is 1700 nm or less, and the average length of the compound particle is 140 nm or less. In many samples, the average grain size of the crystal grains is 1500 nm or less. In the specific sample group (I-1), the average grain size of the crystal grains is 1000 nm or less, and here, further 600 nm or less. In such a specific sample group I, it is thought that the grain boundary strengthening by the fine crystal grains was satisfactorily achieved, so that the mechanical properties (particularly, Vickers hardness and tensile strength) at room temperature and heat resistance were improved.

[0184] In the specific sample group I, the average length of the compound particle is 100 nm or less, and here it is even as small as 60 nm. In addition, the aspect ratio of the compound particle is 3.5 or less, and many samples have an aspect ratio of 3.0 or less. It can be said that such a compound particle is not needle-shaped. Further, the average number of the compound particles present per unit area is 10 or more, and there are many samples having 20 or more. In the specific sample group (I-1), the average number of the compound particles is 25 or more, and there are many samples having 30 or more. There are even samples having an average number of the compound particles of 100 or more. In addition, the average number of the compound particles present per unit area is 220 or less. Since the compound particle is appropriately present, it is considered that elongation is excellent while also having high strength and high hardness.

[0185] In addition, the following can be understood.

1) When the Fe content is less than 1.2 atom%, compared with the specific sample group I, the Vickers hardness and tensile strength at room temperature are lower and the heat resistance is worse (see, for example, a comparison of Samples No. 27 to No. 29 with Samples No. 32 to No. 34).

2) When the Fe content is more than 6.5 atom%, compared with the specific sample group I, the Vickers hardness and tensile strength at room temperature are lower and the heat resistance is also worse (see, for example, a comparison of Samples No. 47 to No. 49 with Samples No. 42 to No. 44). Further, when the Fe content is more than 6.5 atom%, compared with the specific sample group I, the elongation at break at room temperature is lower and the toughness is worse (same comparison).

3) When the content of the first element is less than 0.005 atom% (here, the first element is not included), compared with the specific sample group I, the Vickers hardness and tensile strength at room temperature are lower and the heat resistance is worse (see, for example, a comparison between Sample No. 36 and Sample No. 37).

4) When the content of the first element is more than 0.15 atom%, compared with the specific sample group I, the elongation at break at room temperature is smaller and the toughness is worse (see, for example, a comparison between Sample No. 39 and Sample No. 40). The tensile strength at room temperature and at a high temperature is also lower (same comparison).

5) In the specific sample group I, the higher the Fe content and the higher the content of the first element, the higher the Vickers hardness and tensile strength at room temperature tend to be, and the better the heat resistance tends to be. Conversely, the smaller the Fe content and the smaller the content of the first element, the higher the elongation at break at room temperature tends to be.

6) One of the causes of the difference in mechanical properties is considered to be the difference in structure, such as the size of the crystal grains and the size, shape, and number of the compound particle.

[0186] [c] Next, Tables 11 to 22 will be looked at. Basically, samples having the same composition are compared.

[0187] Below, of Sample No. 116 to 158, the samples other than Sample No. 120, No. 125, No. 131, No. 135, No. 138, No. 141, No. 144, No. 147, No. 150, No. 153, and No. 156 are referred to as specific sample group II.

[0188] In particular, Sample No. 118, No. 123 and No. 127 are called as a specific sample group (II-1).

[0189] As shown in the even-numbered tables, it can be seen that the Al alloy materials that include Fe and the first element in the above-described ranges and include the second element in an amount of 0.005 atom% or more and less than 2 atom% tend to have improved mechanical properties at room temperature and heat resistance.

[0190] In the specific sample group II, the Vickers hardness at 25°C is 93 Hv or more. Many samples have a Vickers hardness of 100 Hv or more. In the specific sample group (II-1) having a high solidification rate, the above-described Vickers hardness is 120 Hv or more.

[0191] In the specific sample group II, the tensile strength at 25°C is 270 MPa or more. Many samples have a tensile

strength of 290 MPa or more, and further 300 MPa or more. Some samples have a tensile strength of 320 MPa or more, and further 350 MPa or more. In the specific sample group (II-1), the tensile strength is 400 MPa or more, and here, further 420 MPa or more.

[0192] In the specific sample group II, the elongation at break at 25°C is 5% or more. There are many samples in which the extension at break is 5.5% or more, and further 6.0% or more.

[0193] In the specific sample group II, the temperature coefficient of Vickers hardness is 0.25%/°C or less. Many samples have a temperature coefficient of 0.24%/°C or less, and further 0.23%/°C or less. For such a specific sample group II, it can be said that Vickers hardness is less likely to decrease even at 250°C, the Vickers hardness is higher as shown in the even-numbered tables (e.g., 40 Hv or more), and heat resistance is even better. Since the Vickers hardness at 25°C is as high as 93 Hv or more, it is considered that the Vickers hardness is likely to be high even at 250°C.

[0194] In the specific sample group II, the rate of decrease in tensile strength from 25°C to 250°C is less than 0.28%/°C, and here it is further 0.26%/°C or less. For such a specific sample group II, it can be said that tensile strength is less likely to decrease even at 250°C, and the tensile strength is higher as shown in the even-numbered tables (e.g., many sample are 120 MPa or more, or 140 MPa or more), and heat resistance is even better.

[0195] In the specific sample group II, the compound particle and the crystal grains tend to be finer. Specifically, the average grain size of the crystal grains is 1500 nm or less, and the average length of the compound particle is 60 nm or less. In many samples, the average grain size of the crystal grains is 1400 nm or less. There are samples in which the average grain size of the crystal grains is 1300 nm or less, and there are even samples in which the average grain size is 1000 nm or less. In the specific sample group (II-1), the average grain size of the crystal grains is 600 nm or less, and here, further 500 nm or less. In such a specific sample group II, it is thought that the grain boundary strengthening by the fine crystal grains was further satisfactorily achieved, so that the mechanical properties (particularly, Vickers hardness and tensile strength) at room temperature and heat resistance were further improved.

[0196] In the specific sample group II, there are many samples in which the average length of the compound particle is 40 nm or less. In addition, the aspect ratio of the compound particle is 2.0 or less, and many samples have an aspect ratio of 1.8 or less. It can be said that such a compound particle is not needle-shaped, and is close to spherical. Further, the average number of the compound particles present per unit area is 40 or more, and there are many samples in which the average number of the compound particles present per unit area is 50 or more, and further 60 or more. In the specific sample group (II-1), the average number of the compound particles is 100 or more, and here, further 150 or more and 200 or more. Further, the average number of the compound particles present per unit area is 530 or less. It can be said that the specific sample group (II-1) has a structure in which a large number of the finer compound particle are dispersed. Since each compound particle is unlikely to be the starting point of cracking, it is considered that elongation is likely to be increased.

[0197] In addition, the following can be understood.

1) When the content of the second element is 0.005 atom% or more, and preferably 0.10 atom% or more, compared with the specific sample group I, at least one of tensile strength and Vickers hardness even at a high temperature is higher, and heat resistance is better (see, for example, a comparison of Sample No. 37 with Samples No. 116 to No. 119).

2) When the content of the second element is less than 2 atom%, and here further when it is 1 atom% or less, the toughness at room temperature is also excellent (see, for example, a comparison between Sample No. 120 and Sample No. 119). When the content of the second element is 0.2 atom% or less, the toughness at room temperature is even better.

3) In the specific sample group II, the higher the content of the second element, the higher the Vickers hardness and tensile strength at room temperature tend to be, and the better the heat resistance tends to be. Conversely, the smaller the content of the second element, the higher the elongation at break at room temperature tends to be.

4) One of the causes of the difference in mechanical properties is considered to be the difference in structure, such as the size of the crystal grains and the size, shape, and number of the compound particle.

[0198] From the above, it was shown that an Al alloy material composed of an Albased alloy that includes a relatively large amount of Fe and a small amount of the first element has excellent heat resistance. Further, it was shown that the Al alloy material has excellent mechanical properties at room temperature. In particular, the Al alloy material can be said to have good heat resistance when the crystal grains forming the matrix are fine and a fine compound particle is dispersed in the matrix.

[0199] Further, it was shown that the Al alloy material having excellent heat resistance can be produced by using a powder or the like produced through quenching of a molten metal to produce a dense intermediate material (relative density of 85% or more), and subjecting this intermediate material to plastic working or the like in state heated to a predetermined temperature.

[0200] The present invention is not limited to these examples. The present invention is defined by the scope of the

claims, and it is intended that all modifications within the meaning and scope equivalent to the claims be included.

[0201] For example, in Test Example 1, the Fe content, the content of the first element, the content of the second element, the production conditions (cooling rate of the molten metal, working temperature and applied pressure at the time of molding, and the like), the shape and dimensions of the Al alloy material, and the like can be modified as appropriate.

Claims

1. An aluminum alloy material comprising:

1.2 atom% or more and 6.5 atom% or less of Fe; and
0.005 atom% or more and less than 0.15 atom% of one or more elements selected from the group consisting of Nd, W, and Sc,
with the balance being Al and unavoidable impurities.

2. The aluminum alloy material according to claim 1, wherein

the aluminum alloy material comprises a structure including a matrix that includes 99 atom% or more of Al and a particle that is present in the matrix and that is composed of a compound including Al and Fe, and
in an arbitrary cross section of the aluminum alloy material, an average grain size of crystal grains forming the matrix is 1700 nm or less and an average length of the particle composed of the compound is 140 nm or less.

3. The aluminum alloy material according to claim 2, wherein, in the cross section, when the area of a square region having a side length of 500 nm is taken as a unit area, an average number of the particles composed of the compound present per unit area is 10 or more and 220 or less.

4. The aluminum alloy material according to claim 2 or 3, wherein the particle composed of the compound has an aspect ratio of 3.5 or less.

5. The aluminum alloy material according to any one of claims 1 to 4, wherein

a Vickers hardness at 25°C is 85 Hv or more, and
a temperature coefficient relating to a decrease in the Vickers hardness from 25°C to 250°C is 0.30% /°C or less.

6. The aluminum alloy material according to any one of claims 1 to 5, wherein an elongation at break at 25°C is 3% or more.

7. An aluminum alloy material comprising:

1.2 atom% or more and 6.5 atom% or less of Fe;
0.005 atom% or more and less than 0.15 atom% of one or more first elements selected from the group consisting of Nd, W, and Sc; and
0.005 atom% or more and less than 2 atom% of one or more second elements selected from the group consisting of C and B,
with the balance being Al and unavoidable impurities.

8. The aluminum alloy material according to claim 7, wherein

the aluminum alloy material comprises a structure including a matrix that includes 99 atom% or more of Al and a particle that is present in the matrix and that is composed of a compound including Al and Fe, and
in an arbitrary cross section of the aluminum alloy material, an average grain size of crystal grains forming the matrix is 1500 nm or less and an average length of the particle composed of the compound is 60 nm or less.

9. The aluminum alloy material according to claim 8, wherein, in the cross section, when the area of a square region having a side length of 500 nm is taken as a unit area, an average number of the particles composed of the compound present per unit area is 40 or more and 530 or less.

10. The aluminum alloy material according to claim 8 or 9, wherein the particle composed of the compound has an

aspect ratio of 2.0 or less.

11. The aluminum alloy material according to any one of claims 1 to 10, wherein

a Vickers hardness at 25°C is 93 Hv or more, and
a temperature coefficient relating to a decrease in the Vickers hardness from 25°C to 250°C is 0.25% /°C or less.

12. The aluminum alloy material according to any one of claims 1 to 11, wherein an elongation at break at 25°C is 5% or more.

13. The aluminum alloy material according to any one of claims 1 to 12, wherein a rate of decrease in tensile strength from 25°C to 250°C is less than 0.28% /°C.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2019/049979

A. CLASSIFICATION OF SUBJECT MATTER
Int. Cl. C22C21/00(2006.01)i, B22D11/06(2006.01)n, B22F3/02(2006.01)n, B22F3/14(2006.01)n, B22F9/08(2006.01)n
FI: C22C21/00 M, B22D11/06 330, B22F3/02 A, B22F3/14 A, B22F9/08 A
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
Int. Cl. B22F3/02, B22F3/14, B22F9/08, C22C21/00, B22D11/06

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2020
Registered utility model specifications of Japan 1996-2020
Published registered utility model applications of Japan 1994-2020

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 1-149935 A (FURUKAWA ALUM CO., LTD.) 13 June 1989, claims	1-13
A	JP 6-21326 B2 (MASUMOTO, Takeshi) 23 March 1994, claims, page 5, column 9, line 33 to column 10, line 26, fig. 1	1-13
A	JP 2018-12869 A (NIPPON LIGHT METAL CO., LTD.) 25 January 2018, claims	1-13
A	CN 102978468 A (ANHUI JOY SENSE CABLE CO., LTD.) 20 March 2013, claims	1-13
P, A	WO 2019/135372 A1 (SUMITOMO ELECTRIC INDUSTRIES, LTD.) 11 July 2019, claims	1-13

☐ Further documents are listed in the continuation of Box C.
☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
05.03.2020	17.03.2020
Name and mailing address of the ISA/ Japan Patent Office 3-4-3, Kasumigaseki, Chiyoda-ku, Tokyo 100-8915, Japan	Authorized officer Telephone No.

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2019/049979

Patent Documents referred to in the Report	Publication Date	Patent Family	Publication Date
JP 1-149935 A	13.06.1989	(Family: none)	
JP 6-21326 B2	23.03.1994	EP 339676 A1 claims, page 6, line 51 to page 7, line 5, fig. 1 US 5053085 A	
JP 2018-12869 A	25.01.2018	(Family: none)	
CN 102978468 A	20.03.2013	(Family: none)	
WO 2019/135372 A1	11.07.2019	(Family: none)	

Form PCT/ISA/210 (patent family annex) (January 2015)

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 2019028568 A **[0001]**
- JP 6158211 A **[0002] [0003]**
- JP 2000096176 A **[0002] [0003]**