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(19) **United States**(12) **Patent Application Publication**
MAEDA(10) **Pub. No.: US 2021/0310102 A1**(43) **Pub. Date: Oct. 7, 2021**(54) **ALUMINUM ALLOY MATERIAL AND
METHOD FOR PRODUCING ALUMINUM
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ABSTRACT

An aluminum alloy material has a composition containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities, and a structure including a matrix and a compound. The matrix is composed mainly of Al, the compound contains Al and Fe, and a relative density is 85% or more. In any cross section, the matrix has an average crystal grain size of 1,100 nm or less, and the compound has an average major-axis length of 100 nm or less.

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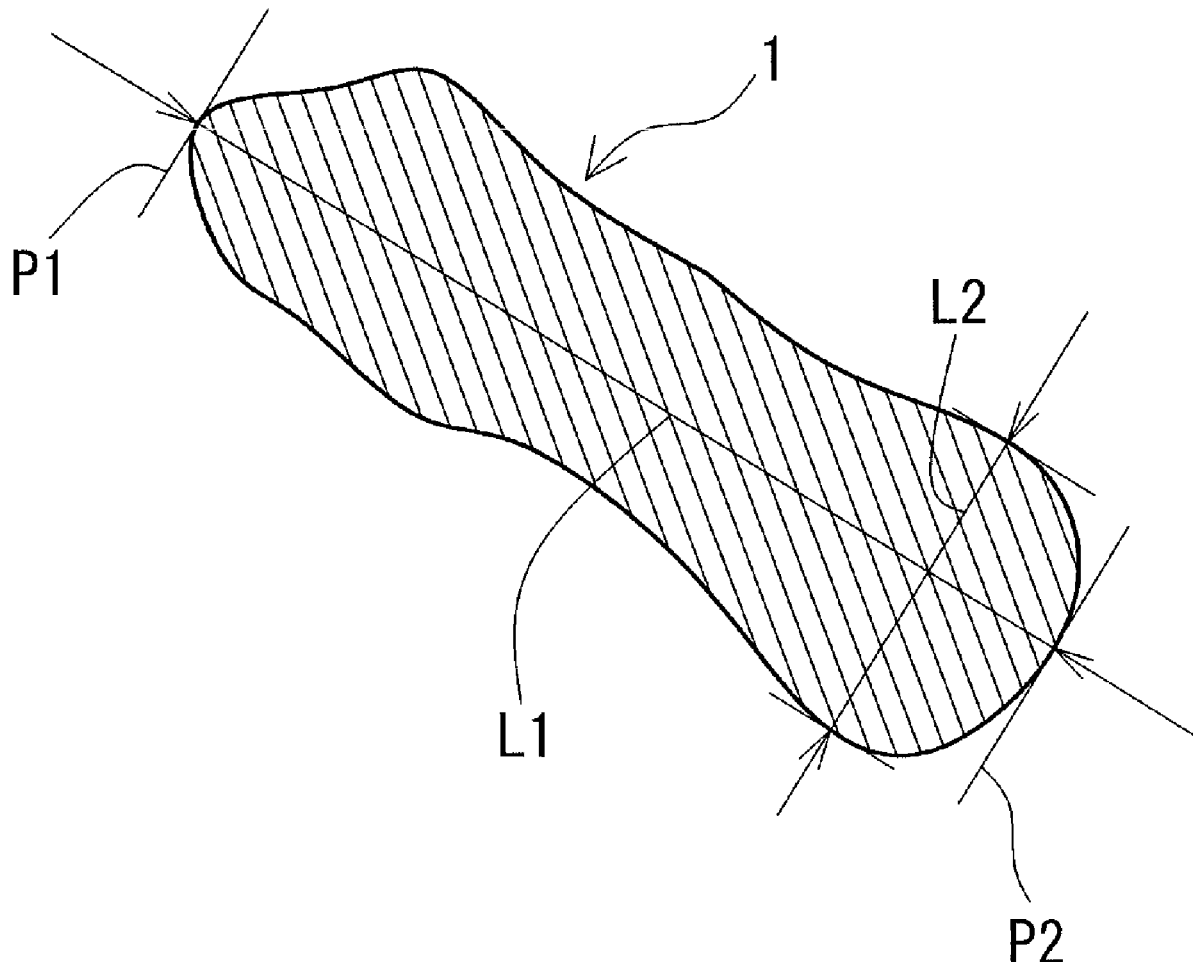
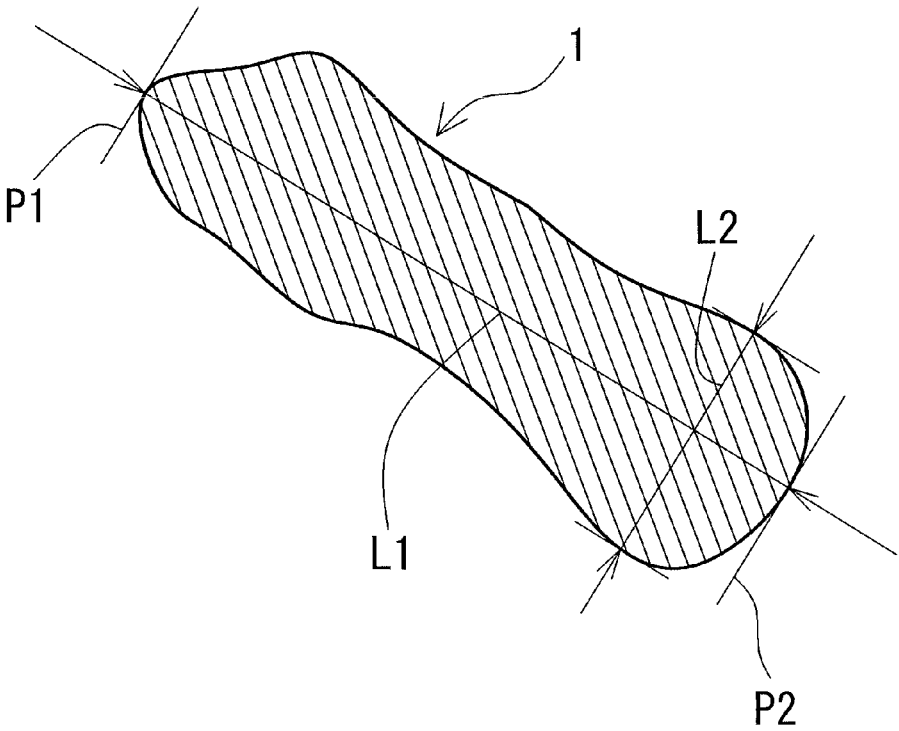


FIG. 1



ALUMINUM ALLOY MATERIAL AND METHOD FOR PRODUCING ALUMINUM ALLOY MATERIAL

TECHNICAL FIELD

[0001] The present disclosure relates to an aluminum alloy material and a method for producing an aluminum alloy material.

[0002] The present application claims priority from Japanese Patent Application No. 2018-filed on Jul. 2, 2018, and the entire contents of the Japanese patent application are incorporated herein by reference.

BACKGROUND ART

[0003] Patent Literature 1 discloses a composite material obtained by forming a powder composed of an aluminum alloy and impregnating the resulting powder compact with an aluminum alloy. Specifically, a compact having a void ratio of 20% by volume is prepared by using a rapidly solidified powder composed of an aluminum alloy containing 40% by mass or less of Fe, Mg, and Cu in total and 60% by mass or more of Al. After the compact is preheated at 500° C., voids of the compact are impregnated with an aluminum alloy (ADC12) to thereby produce the composite material.

CITATION LIST

Patent Literature

[0004] PTL 1: Japanese Unexamined Patent Application Publication No. 2001-073055

SUMMARY OF INVENTION

[0005] An aluminum alloy material according to the present disclosure has

[0006] a composition containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities; and

[0007] a structure including a matrix and a compound,

[0008] in which the matrix is composed mainly of Al,

[0009] the compound contains Al and Fe,

[0010] a relative density is 85% or more, and

[0011] in any cross section, the matrix has an average crystal grain size of 1,100 nm or less, and the compound has an average major-axis length of 100 nm or less.

[0012] A method for producing an aluminum alloy material according to the present disclosure includes

[0013] a step of rapidly cooling a melt of an aluminum alloy containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities to produce a powdery or flaky material in which the Fe is dissolved;

[0014] a step of subjecting the material to warm forming at a temperature of 400° C. or lower to form a dense body having a relative density of 85% or more; and

[0015] a step of subjecting the dense body to heat treatment at a temperature of 400° C. or lower.

[0016] Another method for producing an aluminum alloy material according to the present disclosure includes

[0017] a step of rapidly cooling a melt of an aluminum alloy containing 3% by mass or more and 10% by mass or

less of Fe and the balance of Al and incidental impurities to produce a powdery or flaky material in which the Fe is dissolved;

[0018] a step of subjecting the material to cold forming to form a dense body having a relative density of 85% or more; and

[0019] a step of subjecting the dense body to heat treatment at a temperature of 400° C. or lower.

BRIEF DESCRIPTION OF DRAWING

[0020] FIG. 1 is a view for explaining a method for measuring a major-axis length of a compound containing Al and Fe.

DESCRIPTION OF EMBODIMENTS

Problems to be Solved by Present Disclosure

[0021] An aluminum alloy material having good elongation as well as high strength has been desired. Furthermore, the aluminum alloy material preferably also has high productivity.

[0022] Patent Literature 1 discloses that the composite material obtained by impregnating the compact having voids with an aluminum alloy has higher strength than a wrought material having the same composition. However, the composite material cannot have high strength unless the compact is impregnated with an aluminum alloy. Patent Literature 1 does not describe a configuration having good elongation.

[0023] Furthermore, the composite material requires impregnation with the aluminum alloy and has poor productivity. In addition, it is necessary to reliably form open pores in the compact such that the compact can be impregnated with the aluminum alloy, and thus the composite material also has poor formability.

[0024] Accordingly, an object of the present disclosure is to provide an aluminum alloy material having good elongation as well as high strength. Another object of the present disclosure is to provide a method for producing an aluminum alloy material, the method being capable of producing an aluminum alloy material having good elongation as well as high strength.

Advantageous Effects of Present Disclosure

[0025] The aluminum alloy material according to the present disclosure has good elongation as well as high strength. The method for producing an aluminum alloy material according to the present disclosure can produce an aluminum alloy material having good elongation as well as high strength with high productivity.

DESCRIPTION OF EMBODIMENTS OF PRESENT DISCLOSURE

[0026] First, embodiments of the present disclosure will be listed and described.

[0027] (1) An aluminum alloy material according to an embodiment of the present disclosure has a composition containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities; and

[0028] a structure including a matrix and a compound,

[0029] in which the matrix is composed mainly of Al,

[0030] the compound contains Al and Fe,

[0031] a relative density is 85% or more, and

[0032] in any cross section, the matrix has an average crystal grain size of 1,100 nm or less, and the compound has an average major-axis length of 100 nm or less.

[0033] The average crystal grain size of the matrix and the average major-axis length of the compound are dimensions measured in any cross section of the Al alloy material. Details of methods for measuring the average crystal grain size and the average major-axis length will be described in Test Example 1 described later.

[0034] The aluminum alloy material (hereinafter, also referred to as Al alloy material) according to the present disclosure has good elongation as well as high strength for reasons (a) to (d) described below.

(a) The Fe content satisfies the particular range, and the Al alloy material contains Fe in a relatively large amount.

(b) Iron (Fe) is present mainly as a compound with Al, typically, an intermetallic compound such as $\text{Al}_{13}\text{Fe}_4$. In addition, the compound is a very fine particle having an average major-axis length of 100 nm or less. The compound is typically a precipitate.

(c) The matrix has a very fine crystalline structure having an average crystal grain size of 1,100 nm or less.

(d) The Al alloy material has a high relative density of 85% or more and is dense.

[0035] More specifically, in the Al alloy material according to the present disclosure, since the matrix is formed of very fine crystals, the strength-improving effect due to grain boundary strengthening is obtained. Furthermore, although the Al alloy material according to the present disclosure contains Fe in a relatively large amount, Fe is present mainly as a very fine compound. Since the compound is present in a fine crystalline structure in a dispersed manner, the strength-improving effect due to dispersion strengthening of the compound is obtained. Furthermore, the Al alloy material according to the present disclosure includes an aluminum alloy having a structure subjected to grain boundary strengthening of crystals and dispersion strengthening of the compound, the aluminum alloy being densely present. There provide the Al alloy material according to the present disclosure with good strength. Typically, the Al alloy material according to the present disclosure has a tensile strength higher than that of a wrought material having the same composition by 8.5% or more, further, 10% or more, and thus has good strength. Depending on, for example, the Fe content, the relative density, and production condition, the tensile strength can be made higher than that of the wrought material having the same composition by 10% or more, further, 30% or more.

[0036] In the Al alloy material according to the present disclosure, since Fe is present mainly as a compound, the matrix has a relatively low Fe content. As a result, the matrix can exhibit a ductile deformation behavior. Furthermore, since the compound has a sufficiently small size, a stress concentration is unlikely to occur. Therefore, the compound substantially does not become a starting point of cracking. Such an Al alloy material according to the present disclosure can have high elongation, that is, an elongation at break of 1% or more, further, 2% or more as well as good strength.

[0037] The Al alloy material according to the present disclosure has strength and elongation in a balanced manner because Fe is appropriately present mainly as a very fine compound. It is expected that such an Al alloy material according to the present disclosure can be suitably used as

various structural materials for which a reduction in the weight and high strength/high toughness are desired.

[0038] Furthermore, when the Al alloy material according to the present disclosure is produced by a method for producing an Al alloy material according to an embodiment of the present disclosure described below, high productivity is also achieved. This is because a compact need not be prepared so as to have open pores, a compact having a predetermined shape is easily obtained, and the above-described impregnation step is also unnecessary.

[0039] (2) In an Al alloy material according to an embodiment of the present disclosure,

[0040] the average crystal grain size is 600 nm or less, and the average major-axis length is 35 nm or less.

[0041] In this embodiment, crystal grains and the compound containing Al and Fe are finer. Accordingly, in this embodiment, the compound is easily uniformly dispersed in the crystalline structure, and higher strength is achieved on the basis of dispersion strengthening of the compound and grain boundary strengthening of fine crystal grains. In this embodiment, the compound is unlikely to become a starting point of cracking, and elongation is also further enhanced.

[0042] (3) In an Al alloy material according to an embodiment of the present disclosure,

[0043] when a plurality of square measurement regions each having a side length of 500 nm are chosen in the cross section, an average number of the compounds having a major-axis length of 5 nm or more and 100 nm or less in the measurement regions is 10 or more.

[0044] Details of a method for measuring the average number will be described in Test Example 1 described later.

[0045] In this embodiment, since the above-described very fine compound is present in the particular range, the strength-improving effect due to dispersion strengthening is satisfactorily obtained to provide good strength. Although the compound is contained to a certain degree, the compound is very fine as described above and is unlikely to become a starting point of cracking. Accordingly, this embodiment also has good elongation.

[0046] (4) In an embodiment of the Al alloy material according to (3) above,

[0047] the average number is 80 or more and 175 or less.

[0048] In this embodiment, since the above-described very fine compound is present in the particular range, the strength-improving effect due to dispersion strengthening is suitably obtained to provide good strength. In this embodiment, since the amount of the compound is not excessively large, good elongation is also provided.

[0049] (5) In an Al alloy material according to an embodiment of the present disclosure,

[0050] a tensile strength is 300 MPa or more.

[0051] This embodiment has higher tensile strength than a wrought material having the same composition and thus has high strength.

[0052] (6) In an embodiment of the Al alloy material according to (5) above,

[0053] an elongation at break is 1% or more.

[0054] This embodiment has a high tensile strength of 300 MPa or more and a high elongation at break of 1% or more. Thus, this embodiment has good elongation as well as high strength.

[0055] (7) A method for producing an aluminum alloy material (Al alloy material) according to an embodiment of the present disclosure includes

[0056] a step of rapidly cooling a melt of an aluminum alloy containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities to produce a powdery or flaky material in which the Fe is dissolved;

[0057] a step of subjecting the material to warm forming at a temperature of 400° C. or lower to form a dense body having a relative density of 85% or more; and

[0058] a step of subjecting the dense body to heat treatment at a temperature of 400° C. or lower.

[0059] Herein, rapid cooling means that the cooling rate during solidification of the melt satisfies 10,000° C./s or more. This also applies to a method for producing an Al alloy material of (8) described later.

[0060] The present inventor has investigated the conditions under which an Al alloy material having good elongation as well as higher strength than the wrought material having the same composition can be produced with high productivity. As a result, the present inventor has found that a powdery or flaky material produced by a method that enables more rapid cooling than existing continuous casting methods using a movable mold or existing casting methods using a fixed mold can be satisfactorily formed into a dense compact.

[0061] More specifically, when the cooling rate during solidification of the melt is 10,000° C./s or more, the melt can be solidified without having to provide the time for Fe atoms in Al to be concentrated to form a compound of Al and Fe or the time for the compound to be precipitated. In the resulting solidified product, Fe is substantially dissolved in Al that constitutes the matrix. Furthermore, since there is substantially no time for growth of crystals of the matrix, crystals that constitute the matrix in the solidified product are very fine. Examples of such a method that enables rapid cooling include a so-called liquid quenching method and an atomization method. In the liquid quenching method, the atomization method, or the like, the solidified product is obtained in the form of a thin strip or a powder. Such a thin strip or powder formed of the solidified product is considered to have good formability because a coarse precipitate (the compound described above), which may become a starting point of cracking during forming, is not substantially present or the amount thereof is very small. The thin strip may be pulverized into a flake or a powder.

[0062] The present inventor has found that when the compact obtained after forming is subjected to heat treatment at a relatively low temperature, Fe that has been dissolved can be precipitated mainly as a compound with Al, and the compound can be made very fine. The Al alloy material after heat treatment has higher strength than the wrought material having the same composition, due to grain boundary strengthening by the very fine crystalline structure, dispersion strengthening of the very fine compound, and denseness.

[0063] Furthermore, during the heat treatment, the equilibrium amount of dissolved Fe becomes very small with respect to Al, which mainly constitutes the matrix. Therefore, the matrix after heat treatment exhibits a ductile deformation behavior. Furthermore, after heat treatment, the compound has a very fine size. Therefore, the Al alloy material after heat treatment is unlikely to be subjected to a stress concentration during deformation and is unlikely to be cracked. Accordingly, the Al alloy material after heat treatment has good elongation as well as high strength.

[0064] The method for producing an Al alloy material of (7) above and a method for producing an Al alloy material of (8) described below are based on these findings.

[0065] In the method for producing an Al alloy material of (7) above, a powder or a thin strip produced through rapid cooling of a melt is subjected to warm forming and then subjected to heat treatment at a relatively low temperature. This production method enables the production of an Al alloy material which is dense and in which the very fine compound is dispersed in a very fine crystalline structure.

[0066] Specifically, although the powder or the thin strip provided for forming processing has a high Fe content of 3% by mass or more, the powder or the thin strip is substantially free of precipitated Fe and has a very fine crystalline structure, as described above. Such a powder or a thin strip has good formability and can be satisfactorily formed into a dense compact having a relative density of 85% or more.

[0067] In particular, the forming processing is warm forming at 400° C. or lower. Therefore, the material exhibits enhanced plastic deformability and has better formability. Furthermore, at a working temperature of 400° C. or lower, an excessive growth of a precipitate (compound containing Al and Fe) and crystal grains of the matrix in the forming process is easily suppressed. Therefore, after the subsequent heat treatment, the compound and the crystal grains tend to become fine.

[0068] The working temperature in the forming processing is more preferably lower than the precipitation temperature of the compound because the compound is not substantially precipitated, and the material has good formability.

[0069] In the heat treatment after warm forming, if the heat treatment temperature is 400° C. or lower, while Fe is precipitated mainly as a compound with Al, the compound can be made present as a very fine particle. If the heat treatment temperature is 400° C. or lower, the growth of crystal grains of the matrix can be suppressed to provide a very fine crystalline structure even after the heat treatment.

[0070] The Al alloy material obtained after the heat treatment typically has a relative density of 85% or more, in which, in a cross section, an average crystal grain size of the matrix is 1,100 nm or less, and the average major-axis length of the compound is 100 nm or less. Such an Al alloy material has good elongation as well as high strength as described above. Accordingly, the method for producing an Al alloy material of (7) above can produce an Al alloy material having good elongation as well as high strength.

[0071] The method for producing an Al alloy material of (7) above can produce, with high productivity, an Al alloy material having good elongation as well as high strength for reasons (I) to (V) described below.

(I) In the forming process, a dense compact is satisfactorily formed by using a material having good formability.

(II) Since the material provided for forming processing has good plastic deformability, damage of a forming tool such as a forming die is reduced.

(III) Thermal energy necessary for warm forming and heat treatment is relatively small.

(IV) It is not necessary to perform forming such that the compact has open pores. The above-described impregnation step is unnecessary.

(V) In the compact before heat treatment, the compound is not substantially present or the amount of the compound is very small and the compound is fine, and the crystal grains

are also very fine. Therefore, the compact before heat treatment is easily subjected to cutting work for forming a final shape.

[0072] (8) A method for producing an Al alloy material according to another embodiment of the present disclosure includes

[0073] a step of rapidly cooling a melt of an aluminum alloy containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities to produce a powdery or flaky material in which the Fe is dissolved;

[0074] a step of subjecting the material to cold forming to form a dense body having a relative density of 85% or more; and

[0075] a step of subjecting the dense body to heat treatment at a temperature of 400° C. or lower.

[0076] The method for producing an Al alloy material of (8) above can produce an Al alloy material having good elongation as well as high strength because a material produced through rapid cooling of a melt is used, and after forming, heat treatment is performed at a relatively low temperature as in the method for producing an Al alloy material of (7) above. The details are as described above.

[0077] In particular, in the method for producing an Al alloy material of (8) above, forming processing of the obtained powder or thin strip is performed by cold forming. In cold forming, a precipitate (compound containing Al and Fe) is not substantially precipitated, and crystal grains are also not substantially grown during forming. Therefore, degradation of formability due to a coarse precipitate or coarse crystal grains is unlikely to be caused, and forming processing can be performed.

[0078] The method for producing an Al alloy material of (8) above can produce, with high productivity, an Al alloy material having good elongation as well as high strength due to, for example, good formability, a reduction in thermal energy, the omission of the impregnation step, and good cutting workability, as in the method for producing an Al alloy material of (7) above. When the working temperature in the forming process is around room temperature, thermal energy is not necessary in the forming process, and productivity can be further enhanced.

[0079] (9) In an embodiment of the method for producing an Al alloy material according to (7) or (8) above,

[0080] in X-ray diffraction of the dense body, a peak intensity of a compound containing Al and Fe is $\frac{1}{10}$ or less relative to a peak intensity of an aluminum phase.

[0081] After forming, the dense body has a very small quantity of the compound containing Al and Fe and substantially has an aluminum single phase. Such a material has good cutting workability and can be worked to have a predetermined shape with high accuracy even when the final shape of the Al alloy material is complex. Accordingly, this embodiment can produce, with high productivity, an Al alloy material having good elongation as well as high strength and having high shape accuracy.

DETAILS OF EMBODIMENTS OF PRESENT DISCLOSURE

[0082] Embodiments of the present disclosure will be described in detail below.

[Aluminum Alloy Material]

(Outline)

[0083] An aluminum alloy material (Al alloy material) according to an embodiment is a compact composed of an aluminum-based alloy (Al-based alloy).

[0084] Qualitatively, the Al alloy material according to an embodiment is a dense compact that has a particular composition containing Fe in a relatively large amount and that has a particular structure in which Fe is present mainly as a very fine precipitate and the matrix is a very fine crystalline structure. Quantitatively, the Al alloy material according to an embodiment has a composition containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities. The Al alloy material according to an embodiment has a structure including a matrix composed mainly of Al and a compound containing Al and Fe. The compound is dispersed in the matrix. In a cross section of the Al alloy material, the matrix has an average crystal grain size of 1,100 nm or less, and the compound has an average major-axis length of 100 nm or less. Furthermore, the Al alloy material according to an embodiment has a relative density of 85% or more.

[0085] Details will be further described below.

(Composition)

<Fe>

[0086] An Al alloy material according to an embodiment is composed of an Al-based alloy containing Fe as an additive element, in particular, a binary alloy of Al and Fe. Iron (Fe) satisfies the following conditions (a) and (b).

(a) An amount of Fe dissolved in Al at 660° C. and 1 atmospheric pressure (equilibrium state) is 0.5% by mass or less.

(b) Iron (Fe) forms an intermetallic compound with Al. A compound (for example, $\text{Al}_{13}\text{Fe}_4$) having the lowest Fe element ratio among binary intermetallic compounds of Al and Fe has a melting point of 1,100° C. or higher.

[0087] Such Fe is contained in the particular range, and, in the production process, Fe can be dissolved in an aluminum phase (Al) that constitutes the matrix by, for example, rapidly cooling a melt. When this solid-solution product is subjected to, for example, heat treatment, Fe can be precipitated as a compound (regarding the details, refer to the production methods described below). The compound having even the lowest Fe element ratio has a melting point of higher than or equal to 1,100° C., which is significantly higher than the melting point of the matrix. Such a compound has good stability and thus is easily precipitated. Furthermore, in general, the compound is harder than Al. Such a compound that is present in the matrix in a dispersed manner can function as a strengthening phase of the alloy.

[0088] When the Fe content of the Al-based alloy is 3% by mass or more, the strength-improving effect due to dispersion strengthening (precipitation strengthening) of the compound is appropriately obtained by causing Fe to be present mainly as a compound (precipitate) with Al. In particular, in the Al alloy material according to an embodiment, the strength-improving effect due to dispersion strengthening of the compound containing Fe is appropriately obtained compared with the strength-improving effect due to solid-solution strengthening of Fe in an Al-based alloy containing Fe

in an amount of less than 3% by mass. This is because, in the Al alloy material according to an embodiment, the compound is very fine and is dispersed in a very fine crystalline structure. With an increase in the Fe content, the amount of the compound tends to increase. Therefore, the strength-improving effect due to dispersion strengthening is easily satisfactorily obtained. As a result, the Al alloy material has better strength. Quantitatively, an amount of increase in tensile strength relative to tensile strength of a wrought material having the same Fe content may be 8.5% or more, further, 10% or more, and 30% or more.

[0089] On the other hand, when the Fe content of the Al-based alloy is 10% by mass or less, the compound is unlikely to become coarse. Therefore, the generation of cracking due to a coarse compound is suppressed. As a result, the Al alloy material easily has an enhanced elongation while having good strength. In addition, when the Fe content is small to a certain degree, the Al alloy material has high productivity. In the case of production by the method for producing an Al alloy material according to an embodiment described later, a material having good formability described later is easily produced.

[0090] When the Fe content is 3.5% by mass or more, further, 3.8% by mass or more, and 4.0% by mass or more, the Al alloy material has higher strength. When the Fe content is 9.8% by mass or less, further, 9.5% by mass or less, and 9.0% by mass or less, the Al alloy has better elongation. When the Fe content is 3.5% by mass or more and 9.8% by mass or less, further, 4.0% by mass or more and 9.0% by mass or less, the Al alloy material can have high strength and high toughness in a balanced manner.

[0091] The term “Fe content” as used herein refers to the amount contained in an Al-based alloy that constitutes the Al alloy material. In the production process, when a raw material (typically, aluminum base metal) contains Fe as an impurity, the amount of Fe added to the raw material may be adjusted such that the Fe content satisfies the range of 3% by mass or more and 10% by mass or less.

<Matrix>

[0092] The matrix of the Al-based alloy is a main phase excluding, for example, a precipitate such as a compound containing Al and Fe. The matrix is typically constituted by an aluminum phase (Al), elements dissolved in Al, and incidental impurities.

[0093] The amount of Fe dissolved in the aluminum phase (Al) is preferably small. This is because when Fe is present mainly as a compound with Al and the amount of the compound is large, the strength-improving effect due to dispersion strengthening of the compound is easily obtained. Quantitatively, when the amount of the matrix is assumed to be 100% by mass, the amount of Fe dissolved in the matrix may be 0.5% by mass or less. In this case, the Al content of the matrix is 99.5% by mass or more. Herein, the amount dissolved is an indicator in the rapidly cooled state (non-equilibrium state) described later. If the amount dissolved is very small, namely, 0.5% by mass or less, even in the case where the Fe content is 3% by mass, which is the lower limit value, 80% by mass or more of Fe in the Al-based alloy is present as the compound ($((3-0.5)/3) \times 100 \approx 83$). In an Al-based alloy having a higher Fe content, 90% by mass or more, further, 95% by mass or more of Fe in the Al-based alloy is present as the compound. When the amount dissolved is 0.45% by mass or less, further, 0.40% by mass or

less, and 0.35% by mass or less, the amount of the compound tends to further increase, and the strength tends to further increase.

(Structure)

[0094] The Al-based alloy has a fine structure in which crystal grains constituting a matrix are very fine and which includes very fine particles composed of a compound containing Al and Fe. Since the matrix has a very fine crystalline structure, the strength-improving effect due to grain boundary strengthening is obtained. Since a very fine compound is dispersed in the crystalline structure, the strength-improving effect due to dispersion strengthening of the compound is obtained. These strength-improving structures provide the Al alloy material according to an embodiment with good strength. Furthermore, since the Fe content (the amount of Fe dissolved) in the matrix is small, the Al alloy material exhibits a ductile behavior. In addition, since the compound is very fine, the compound is unlikely to become a starting point of cracking. Such an Al alloy material according to an embodiment also has good elongation.

<Crystal Grain>

[0095] In any cross section of the Al alloy material, crystals constituting the matrix have an average crystal grain size of 1,100 nm or less. An average crystal grain size of 1,100 nm or less means very small crystal grains and a large number of crystal grain boundaries. As a result, slip planes tend to be discontinuous with the crystal grain boundaries therebetween, and the resistance to slipping is enhanced to satisfactorily obtain the strength-improving effect due to grain boundary strengthening. The smaller the average crystal grain size, the more easily the strength-improving effect due to grain boundary strengthening is obtained, and the more easily the strength becomes high. In addition, since the crystal grains are very small, the above-described very fine compound is uniformly easily dispersed, and the strength-improving effect due to dispersion strengthening of the compound is also easily obtained. The smaller the crystal grains, the more easily these effects are obtained. In the case of desiring an improvement of the strength, the average crystal grain size is preferably 1,000 nm or less, further, 800 nm or less, 700 nm or less, and in particular, 600 nm or less. The lower limit is not particularly set. However, considering, for example, productivity, the average crystal grain size may be 300 nm or more, further, 350 nm or more.

<Compound>

«Size»

[0096] In any cross section of the Al alloy material, the compound containing Al and Fe has an average major-axis length of 100 nm or less. An average major-axis length of 100 nm or less means that the compound is not continuous in the Al-based alloy but is present in the form of a very short particle. Such a compound tends to be present in isolation and is easily dispersed in the crystalline structure. The shorter the average major-axis length, the more easily the compound is uniformly dispersed in the crystalline structure. Therefore, the strength-improving effect due to dispersion strengthening of the fine compound is easily obtained. With a decrease in the average major-axis length, the compound is less likely to become a starting point of cracking, and the

elongation is further enhanced. In the case of desiring an improvement of the strength and elongation, the average major-axis length is preferably 95 nm or less, further, 80 nm or less, 50 nm or less, and in particular, 35 nm or less. The lower limit is not particularly set. However, considering, for example, productivity, the average major-axis length may be 10 nm or more, and 15 nm or more.

[0097] In particular, when the matrix has an average crystal grain size of 600 nm or less, and the compound containing Al and Fe has an average major-axis length of 35 nm or less, the Al alloy material has better elongation as well as better strength. This is because the effects of dispersion strengthening due to uniform dispersion of the compound, grain boundary strengthening due to fine crystal grains, and the decrease in cracking are more easily obtained as described above.

«Quantity»

[0098] When a plurality of square measurement regions each having a side length of 500 nm are chosen in any cross section of the Al alloy material, the average number of the compounds having a major-axis length of 5 nm or more and 100 nm or less in the measurement regions is preferably 10 or more. When 10 or more very fine compounds having a major-axis length of 100 nm or less are present on average in a 500 nm×500 nm measurement region, the strength-improving effect due to dispersion strengthening is suitably obtained. Therefore, the Al alloy material has good strength. In addition, the compounds enable the growth of crystal grains to be suppressed, and consequently, the crystal grains readily become finer. For example, the average crystal grain size described above readily becomes 600 nm or less. As a result, the strength-improving effect due to grain boundary strengthening is easily obtained. This also easily increases the strength. Furthermore, although the compounds are included to a certain degree, the compounds are unlikely to become starting points of cracking, because the compounds are very fine and are present in a dispersed manner. Such an Al alloy material also has good elongation.

[0099] The larger the average number of the very fine compounds in the measurement regions, the more easily the strength-improving effect due to dispersion strengthening, further, grain boundary strengthening is obtained, and the more easily the strength increases. When the average number is 30 or more, further, 50 or more, and 70 or more, the strength more easily increases. On the other hand, when the average number is small to a certain degree, the elongation easily increases. When the average number is 200 or less, further, 190 or less, and 180 or less, the elongation easily increases and the elongation at break easily becomes 1% or more.

[0100] In particular, the average number of compounds having a major-axis length of 5 nm or more and 100 nm or less in the measurement region is preferably 80 or more and 175 or less. With an increase in the average number, the strength-improving effects due to dispersion strengthening, and further, grain boundary strengthening are more easily obtained as described above, and the strength more easily increase. When the average number is not excessively large, the generation of cracking originating from the compounds is suppressed, and the elongation more easily increase. Quantitatively, the Al alloy material can have high strength which is a tensile strength of 300 MPa or more, and high elongation which is an elongation at break of 2% or more in

a balanced manner. When the average number is 100 or more and 175 or less, the Al alloy material can have higher strength which is a tensile strength of 320 MPa or more.

[0101] If the average number of the very fine compounds is 10 or more and 200 or less in the measurement region in any cross section of the Al alloy material, anisotropy of the quantity of the compound is small or there is substantially no anisotropy of the quantity of the compound. In such an Al alloy material, the compound is uniformly dispersed.

[0102] The measurement of the amount of dissolved Fe (% by mass) and the determination of the composition of the compound may be conducted by using an apparatus capable of performing local component analysis. Examples of the apparatus include a transmission electron microscope (TEM) and SEM equipped with a measuring apparatus by energy dispersive X-ray spectroscopy (EDX). Alternatively, with regard to materials in which predetermined amounts (about 0% by mass to 1.5% by mass) of Fe is dissolved, structural analysis may be performed by XRD, and the relation between the diffraction angle of an X-ray diffraction peak and the Fe content may be calibrated to derive the amount of dissolved Fe or the like.

«Shape»

[0103] When the shape of the compound is a substantially spherical shape, the compound is easily uniformly dispersed in the crystalline structure and is unlikely to become a starting point of cracking. This is preferred because the Al alloy material has both good strength and good elongation. In the production by the method for producing an Al alloy material according to an embodiment described below, the shape of the compound is typically a substantially spherical shape. Herein, the expression “substantially spherical” may mean that an aspect ratio described below is 1 or more and 2 or less, and preferably 1 or more and 1.5 or less. The aspect ratio refers to a ratio of a major-axis length to a minor-axis length described below. With regard to a compound present in any cross section of an Al alloy material, a maximum length L1 of the compound in this cross section (FIG. 1 described below) is defined as a major-axis length. The maximum length of a line segment orthogonal to the direction of the major axis is defined as a minor-axis length L2 (FIG. 1). If the aspect ratio L1/L2 is close to 1, the compound has small shape anisotropy or substantially no shape anisotropy and is easily uniformly dispersed in the matrix.

<Relative Density>

[0104] The Al alloy material according to an embodiment has a relative density of 85% or more and is dense. Since the Al alloy material is composed of an Al-based alloy having a structure in which a very fine compound is dispersed in the very fine crystalline structure and has a high relative density of 85% or more, the Al alloy material has good elongation as well as high strength. An Al alloy material having a higher relative density has a higher occupancy of the Al-based alloy having the above-described particular composition and particular structure and has less voids. The small number of voids tend to suppress the generation of cracking due to a stress concentration to void portions. This also provides the Al alloy material with good elongation as well as good strength. Therefore, the relative density is preferably 90% or more, further, 92% or more, and more preferably 93% or

more. The use of the method for producing an Al alloy material according to an embodiment described below enables easy production of a dense Al alloy material that has a relative density of 85% or more and that is composed of an Al-based alloy having the above-described particular composition and particular structure.

[0105] Herein, the relative density is determined by using the apparent density and the true density of the Al alloy material with $(\text{apparent density}/\text{true density}) \times 100$. The true density of the Al alloy material may be determined by, for example, performing composition analysis of the Al alloy material and calculating the true density on the basis of the composition of the Al-based alloy. The apparent density is the mass per unit volume determined by using the mass and the volume measured so as to include pores inside the Al alloy material with $(\text{mass}/\text{volume}) \times 100$. The upper limit of the relative density is 100%. When the relative density is 100%, the Al alloy material has the true density.

<Mechanical Properties>

[0106] The Al alloy material according to an embodiment has good elongation as well as high strength.

<Strength>

[0107] With regard to the strength, for example, the tensile strength of the Al alloy material according to an embodiment may be 108.5% or more of the tensile strength of the wrought material having the same composition. In other words, the amount of increase in the tensile strength relative to the tensile strength of the wrought material having the same composition may be 8.5% or more. Such an Al alloy material has higher strength than the wrought material having the same composition. The larger the amount of increase, the higher the tensile strength. For example, the amount of increase may be 10% or more, further, 30% or more.

[0108] A wrought material of an Al-based alloy containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities has a tensile strength of about 210 MPa or more and 230 MPa or less (refer to Test Example described later).

[0109] A tensile strength of 300 MPa or more is still higher than the tensile strength of the wrought material having the same composition. In this case, the amount of increase is 30% or more, and the Al alloy material has better strength. The tensile strength is more preferably 310 MPa or more, further, 315 MPa or more, and 320 MPa or more. On the other hand, if the tensile strength is excessively high, the elongation at break tends to become excessively low. When the tensile strength is 500 MPa or less, further, 450 MPa or less, the Al alloy material has good elongation as well as high strength. Herein, the tensile strength and the elongation at break described later are values at room temperature (for example, 25° C.).

<Elongation>

[0110] With regard to elongation, for example, the Al alloy material according to an embodiment may have an elongation at break of 1% or more. An elongation at break of 1% or more means good elongation. The elongation at break is more preferably 1.5% or more, further, 1.8% or more, and 2.0% or more. On the other hand, if the elongation at break is excessively high, the tensile strength tends to become

excessively low. When the elongation at break is 10% or less, further, 5% or less, the Al alloy material has good elongation as well as high strength.

[0111] In particular, an Al alloy material having a tensile strength of 300 MPa or more and an elongation at break of 1% or more is preferred because the Al alloy material has good elongation as well as high strength.

[0112] The average crystal grain size, the major-axis length and the number of the compounds, and the tensile strength and the elongation at break of the Al alloy material can be changed by adjusting, for example, the Fe content, the relative density, and production conditions (for example, heat treatment conditions). For example, if the amount of Fe is large in the range described above, the average crystal grain size, and the major-axis length and the number of the compounds tend to increase. If the amount of Fe is small in the range described above, the opposite tendency is exhibited. For example, if the amount of Fe is large in the range described above, the tensile strength tends to increase. If the amount of Fe is small in the range described above, the elongation at break tends to increase.

<Applications>

[0113] The Al alloy material according to an embodiment can have various shapes and sizes. In the production process, for example, the shape of a forming die and cutting work after forming may be selected such that the Al alloy material has a predetermined shape and a predetermined size. Examples of the typical shape of the Al alloy material include solid bodies such as a wire rod, a bar, and a plate; and cylindrical bodies having a through-hole. The size of the Al alloy material can be appropriately selected according to the intended application and the like.

(Main Advantageous Effects)

[0114] The Al alloy material according to an embodiment has good elongation as well as high strength. This advantageous effect will be specifically described in Test Example 1 described later. In addition, when the Al alloy material according to an embodiment is produced by a method for producing an Al alloy material according to an embodiment described below, high productivity is also achieved.

[Method for Producing Al Alloy Material]

(Outline)

[0115] The Al alloy material according to an embodiment may be produced by, for example, a method (A) or (B) for producing an Al alloy material according to an embodiment, the method (A) or (B) including a material preparation step, a forming step, and a heat treatment step described below. In short, the production methods (A) and (B) each include forming a material produced through rapid cooling of a melt, and subjecting the formed dense body to heat treatment at a relatively low temperature. However, a working temperature in the forming process is different between the production methods (A) and (B). In the production method (A), a material produced through rapid cooling of a melt is subjected to warm forming to thereby produce a dense body. In the production method (B), the material is subjected to cold forming to thereby produce a dense body.

[0116] Production Method (A)

(Material Preparation Step) A melt of an aluminum alloy containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities is rapidly cooled to produce a powdery or flaky material in which Fe is dissolved.

(Forming Step) The material is subjected to warm forming at a temperature of 400° C. or lower to form a dense body having a relative density of 85% or more.

(Heat Treatment Step) The dense body is subjected to heat treatment at a temperature of 400° C. or lower.

[0117] Production Method (B)

(Material Preparation Step) A melt of an aluminum alloy containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities is rapidly cooled to produce a powdery or flaky material in which Fe is dissolved.

(Forming Step) The material is subjected to cold forming to form a dense body having a relative density of 85% or more.

(Heat Treatment Step) The dense body is subjected to heat treatment at a temperature of 400° C. or lower.

[0118] In the methods (A) and (B) for producing an Al alloy material according to an embodiment, although the Fe content is relatively high, namely, 3% by mass or more, the rapid cooling of the melt provides, for forming processing, a material in which Fe is not substantially precipitated and which has a very fine crystalline structure. Such a material has good formability, can satisfactorily provide a compact (dense body) having a relative density of 85% or more, and has high productivity of the dense body. This is because a coarse compound and coarse crystal grains are not substantially present in the material or the amounts thereof are very small, and this prevents the phenomenon that, during forming, coarse grains become starting points of breakage, resulting in the generation of cracking. In particular, in the production method (A), since warm forming is performed, formability can be further enhanced (details will be described later). In the production method (B), since cold forming is performed, during forming, precipitation and coarse growth of the compound are unlikely to occur.

[0119] In the methods (A) and (B) for producing an Al alloy material according to an embodiment, Fe that has been dissolved in the matrix can be precipitated as a very fine precipitate (compound containing Al and Fe) by subjecting the dense body to heat treatment at a relatively low temperature. Furthermore, the heat treatment at a relatively low temperature enables the growth of crystal grains of the matrix to be suppressed to provide a crystalline structure that is very fine even after the heat treatment. Accordingly, the methods (A) and (B) for producing an Al alloy material according to an embodiment enables production of an Al alloy material in which a very fine compound is dispersed in a very fine crystalline structure, typically, the Al alloy material according to an embodiment.

[0120] The steps will be described in detail below.

(Material Preparation Step)

<Common to (A) and (B)>

[0121] In this step, typically, a melt composed of the Al-based alloy described above is rapidly cooled to produce a solid-solution product in which Fe is substantially dissolved. In existing continuous casting methods, the cooling rate of a melt during casting is 1,000° C./s or less. Practi-

cally, the cooling rate is hundreds of degrees Celsius per second or less. In casting methods using a fixed mold, the cooling rate is usually lower than that in the continuous casting methods and is about 100° C./s or less, although it depends on the size of the cast product. If a melt containing, for example, 3% by mass or more of Fe is solidified at such a cooling rate, a compound containing Al and Fe is precipitated during casting. In particular, a coarse compound or an agglomerate of a compound having an average major-axis length of 200 nm or more, further, 300 nm or more, and 500 nm or more is precipitated. The crystal grains also tend to increase, and the average crystal grain size tends to be 1,200 nm or more, further, 3,000 nm or more. When such a cast product is subjected to, for example, press working, a coarse compound or a coarse crystal grain becomes a starting point of cracking, resulting in degradation of formability. In the method for producing an Al alloy material according to an embodiment, the cooling rate of the melt is higher than that in the existing continuous casting methods in consideration of the Fe content of 3% by mass or more.

<Cooling Rate>

[0122] Qualitatively, the cooling rate during solidification of the melt is a magnitude at which Fe is not substantially precipitated. Quantitatively, the cooling rate is 10,000° C./s or more. A higher cooling rate results in a lower likelihood of precipitation of Fe and more readily provides a solid-solution product (supersaturated solid solution) that substantially does not include a precipitate composed of a compound containing Al and Fe. At a cooling rate of 15,000° C./s or more, further, 20,000° C./s or more, and 50,000° C./s or more, precipitation of Fe is more effectively reduced.

[0123] The cooling rate of the melt may be adjusted on the basis of, for example, the composition of the melt, the temperature of the melt, and the size (such as the powder diameter or the thickness) of the solid-solution product. The cooling rate may be determined by, for example, observing the temperature of the melt in contact with a mold with a high-sensitivity infrared thermographic camera. The infrared thermographic camera may be, for example, an A6750 manufactured by FLIR Systems, Inc. (temporal resolution: 0.0002 sec). The mold may be a copper roll or the like in, for example, a melt-spun method described later. The cooling rate is determined by $(\text{the temperature of the melt} - 300)/t$ (° C./s), wherein t (second) represents the elapsed time of cooling from the temperature (° C.) of the melt to 300° C. For example, when the temperature of the melt is 700° C., the cooling rate is determined by $400/t$ (° C./s).

[0124] When the solid-solution product is produced in the form of a powder or a thin strip, the cooling rate of 10,000° C./s or more is easily achieved due to a small powder diameter or a small thickness. A powdery solid-solution product, a thin strip-like solid-solution product, or a powdery or flaky solid-solution product obtained by pulverizing a thin strip into short pieces has good formability as it is and can be used as a material provided for forming processing. The production methods (A) and (B) use the powdery or flaky solid-solution product as a material.

<Method for Producing Solid-Solution Product>

[0125] A method for producing a thin strip-like solid-solution product is a so-called liquid quenching method. An example of the liquid quenching method is a melt-spun

method. A method for producing a powdery solid-solution product is an atomization method. An example of the atomization method is a gas atomization method.

[0126] In the melt-spun method, a raw material melt is sprayed and rapidly cooled on a cooling medium, such as a roll or disk that rotates at a high speed, to produce a thin strip in which a supersaturated solid solution is continuous in a strip shape. In the melt-spun method, the cooling rate of the melt can be $100,000^{\circ}\text{C./s}$ or more, further, $1,000,000^{\circ}\text{C./s}$ or more, although it depends on, for example, the Fe content and the thickness of the thin strip. The thin strip obtained as described above may be cut or pulverized to provide a flake or a powder. The flake has a length shorter than that of the thin strip. The length of the flake may be, for example, substantially equal to or shorter than the width or the thickness of the thin strip. The material constituting the cooling medium may be, for example, a metal such as copper.

[0127] In the atomization method, a raw material melt is caused to flow through small holes at the bottom of a crucible, and a gas with high cooling power or water is sprayed at a high pressure so that the narrow flow of the melt is scattered and rapidly cooled to produce a powder. The gas may be, for example, argon gas, air, or nitrogen. In the atomization method, the type of the cooling medium (such as the type of gas), the state of the melt (such as the spray pressure and the flow rate), and the temperature are adjusted such that the cooling rate of the melt becomes $10,000^{\circ}\text{C./s}$ or more. In the atomization method, the cooling rate can be $50,000^{\circ}\text{C./s}$ or more, further, $100,000^{\circ}\text{C./s}$ or more, although it depends on, for example, the Fe content and the gas pressure.

[0128] The thickness of the thin strip or the thickness of the flake may be, for example, $100\text{ }\mu\text{m}$ or less, further, $50\text{ }\mu\text{m}$ or less, and $40\text{ }\mu\text{m}$ or less. The diameter (powder diameter) of the atomized powder may be, for example, $20\text{ }\mu\text{m}$ or less, further, $10\text{ }\mu\text{m}$ or less, and $5\text{ }\mu\text{m}$ or less.

<Rolling Step>

[0129] It was found that since the powdery or flaky solid-solution product has a very fine crystalline structure in which Fe is not substantially precipitated as described above, the solid-solution product has good plastic workability and can be satisfactorily subjected to rolling such as so-called powder rolling. A rolled product obtained after rolling is dense and has good formability compared with the solid-solution product before rolling. It was found that this rolled product has good formability to such an extent that a dense compact can be satisfactorily formed even by cold forming. For example, a powder or flake obtained by pulverizing the rolled product can be formed into a dense compact having a relative density of 85% or more even by cold forming. Accordingly, an example of the production method (B) in which forming is performed by cold working may use a material obtained by rolling a powdery or thin strip-like solid-solution product and subsequently pulverizing the resulting rolled product. Regarding conditions for the powder rolling, a pressing pressure and a gap between rolls may be adjusted so as to obtain a rolled product having a predetermined thickness. For example, a rolling mill including a pair of rolls may be used. Regarding the rolling conditions, the diameter of each of the rolls may be about $50\text{ mm}\phi$ to $60\text{ mm}\phi$, the pressing pressure may be about 5 tons, and the gap between the rolls may be 0 mm.

[0130] The thickness of the rolled product produced by powder rolling can be appropriately selected. When the thickness of the rolled product is, for example, about 0.1 mm or more and 1.5 mm or less, further, about 0.3 mm or more and 1.2 mm or less, the rolled product is easily formed. This rolled product may be pulverized after rolling to easily provide a powder or the like. The size of the powder or flake obtained by pulverization can be appropriately selected within a range where forming can be performed. For example, the maximum length of the powder or flake obtained by pulverization may be substantially equal to or less than the thickness of the rolled product, in particular, $50\text{ }\mu\text{m}$ or less.

<Structure of Material>

[0131] The phrase “Fe is not substantially precipitated in a material to be provided for forming processing” may quantitatively mean that when the material is subjected to X-ray diffraction (XRD), the peak intensity of a compound containing Al and Fe is $1/5$ or less relative to the peak intensity of the aluminum phase.

[0132] Herein, in the structural analysis by XRD, the ratio of the top peak intensity of the compound to the top peak intensity of the aluminum phase (Al) (the top peak intensity of the compound/the top peak intensity of Al) corresponds theoretically to the volume ratio, on the assumption that the entire Fe is precipitated. At an ideal ratio, there is not much difference between the denominator and the numerator. In contrast, when the ratio is $1/5$ or less, the numerator (the top peak intensity of the compound) of the ratio is very small compared with the denominator (the top peak intensity of Al) of the ratio. This state is a state in which Fe is not substantially present as the compound but is dissolved.

[0133] At a cooling rate of the melt of $10,000^{\circ}\text{C./s}$ or more, a solid-solution product in which the ratio is $1/5$ or less is easily obtained. The ratio in the above-described material is substantially equal to the ratio in the solid-solution product and does not substantially change even if the solid-solution product is subjected to the powder rolling or the like. The lower the ratio, the higher the proportion of the amount of solid solution in the Fe content, and the lower the proportion of Fe present as the compound. Such a solid-solution product is preferred because the solid-solution product has good formability and is easily formed into a dense compact. Therefore, the ratio is preferably $1/20$ or less. A further increase in the cooling rate or a further decrease in the size (such as the thickness or the powder diameter) of the solid-solution product readily decreases the ratio.

[0134] Even in the case where the material includes the compound containing Al and Fe, the compound is very fine, and the amount thereof is very small. Quantitatively, in a cross section of the material, the average major-axis length of the compound may be 100 nm or less, further, 50 nm or less, and 30 nm or less. In a cross section of the material, with regard to a plurality of measurement regions of $500\text{ nm}\times 500\text{ nm}$, the average number of the compounds having a major-axis length of 100 nm or less may be 150 or less, further, 100 or less, and 50 or less. With regard to the average major-axis length, the section “Size” in “Compound” described above is referred to. With regard to the average number, the section “Quantity” in “Compound” described above is referred to.

[0135] Regarding the size of crystal grains of the matrix in the material, the average crystal grain size may be $1,100\text{ nm}$

or less, further, 1,000 nm or less, and 800 nm or less in a cross section of the material. With regard to this average crystal grain size, the section <Crystal Grain> is referred to.

(Forming Step)

[0136] In this step, the material described above is subjected to forming by warm working or cold working to produce a compact having a relative density of 85% or more. Voids inside the Al alloy material that is finally obtained are reduced by densification. This results in a lower likelihood of occurrence of cracking due to a stress concentration to void portions and enables production of an Al alloy material having good elongation as well as high strength.

<Cold Working>

[0137] In the case where the material is one that has been subjected to the rolling described above, the forming processing may be cold forming, although the forming processing may be warm forming described below. A reason for this is that the material that has been subjected to rolling is dense and has good formability as described above. Another reason is that, in cold forming, a precipitate (compound containing Al and Fe) does not substantially precipitate, or crystal grains do not substantially grow during forming. Accordingly, degradation of formability due to a coarse precipitate or coarse crystal grains is unlikely to occur. The cold forming may be, for example, press forming using a uniaxial pressing machine or the like.

[0138] The working temperature in the cold forming may be, for example, room temperature (about 5° C. to 35° C.). When the working temperature is room temperature, the precipitation of the precipitate and the growth of the crystal grains are prevented. In this respect, cold forming is good in terms of formability. In addition, thermal energy is not necessary in the forming process. In this respect, cold forming is also good in terms of productivity. When the working temperature is, for example, a temperature selected from 150° C. or lower, plastic workability of the material is enhanced and a compact is easily provided.

[0139] The pressure to be applied may be selected in a range where the relative density becomes 85% or more. Quantitatively, the pressure to be applied may be 0.1 GPa or more, further, 0.5 GPa or more, 0.8 GPa or more, and 1.0 GPa or more. From the viewpoint of, for example, preventing cracking due to expansion of inner voids of the compact from occurring and improving durability of the forming die, the pressure to be applied may be 2.0 GPa or less. With an increase in the forming pressure, the relative density tends to increase, and the compact tends to become dense, although it depends on, for example, the composition and the size of the material.

[0140] Typically, the compact (dense body) after forming substantially maintains the structure of the material, and neither a coarse compound nor a coarse crystal grain is substantially present.

<Warm Working>

[0141] In the case where the material is one that is not subjected to the rolling described above, warm forming is preferred. This is because plastic workability of the material is enhanced and a compact is easily formed. The warm forming may be, for example, press forming using a uniaxial pressing machine or the like, so-called hot pressing.

[0142] The working temperature in the warm forming may be, for example, 400° C. or lower. When the working temperature is 400° C. or lower, excessive growth of a compound containing Al and Fe and crystal grains of the matrix is suppressed in the forming process while formability of the material is enhanced, and a dense compact is satisfactorily obtained. Furthermore, after heat treatment described below, an Al alloy material in which a very fine compound is dispersed in a very fine crystalline structure is easily obtained. With a decrease in the working temperature, the growth of the compound and crystal grains tends to be suppressed. Therefore, the working temperature may be 390° C. or lower, further, 380° C. or lower. At a working temperature of 375° C. or lower, preferably, 350° C. or lower, the compound does not substantially precipitate or is unlikely to precipitate. Therefore, a compact (dense body) in which the compound is not substantially precipitated or the compound is very fine and the amount thereof is small and which has good cutting workability as described below is obtained. On the other hand, at a working temperature of 300° C. or higher, plastic workability of the material is further enhanced. With an increase in the working temperature, plastic workability of the material is further enhanced. Thus, the working temperature may be 320° C. or higher.

[0143] The pressure to be applied may be selected within a range where the relative density becomes 85% or more. Quantitatively, the pressure to be applied may be 50 MPa or more, further, 100 MPa (0.1 GPa) or more, and 700 MPa or more. When the pressure to be applied is 1 GPa or more, further, 1.5 GPa or more, a denser compact tends to be obtained. From the viewpoint of, for example, preventing cracking of the compact from occurring and improving durability of a forming die, the pressure to be applied may be 2.0 GPa or less.

[0144] At a working temperature of 400° C. or lower, the compact (dense body) after forming typically has a structure close to the structure of the material. Even if the compound is present, the compound is very fine and the quantity of the compound is also small, and crystal grains are also very fine.

<Relative Density>

[0145] The compact (dense body) has a relative density of 85% or more as described above. The Al alloy material that is finally obtained substantially maintains the relative density of the compact. Therefore, with an increase in the relative density of the compact, a denser Al alloy material having a higher relative density, i.e., an Al alloy material having a better elongation as well as higher strength is obtained. When the compact has a relative density of 90% or more, further, 92% or more, and 93% or more, a denser Al alloy material having higher strength and higher toughness is produced.

<Structure of Compact>

[0146] The compact (dense body) substantially maintains the structure of the material or has a structure close to that of the material, as described above. For example, in XRD of the compact, the peak intensity of the compound containing Al and Fe may be $\frac{1}{10}$ or less relative to the peak intensity of the aluminum phase. The lower the ratio, the lower the proportion of Fe that is present as the compound, as described above. Therefore, a compact having a low ratio has high cutting workability compared with the case where

cutting work is performed after heat treatment described later. For example, even in the case where the final shape is complex, an Al alloy material having high shape accuracy can be produced by subjecting the compact to cutting work. The ratio is preferably $\frac{1}{12}$ or less, further, $\frac{1}{15}$ or less because higher cutting workability is achieved. The ratio tends to be decreased at a lower working temperature during forming.

<Other Forming Processing>

[0147] Another example of forming processing is warm extrusion in which the material described above is extruded at a temperature of 400° C. or lower. The extrusion temperature is preferably 300° C. or higher and 400° C. or lower, further, 380° C. or lower, and 350° C. or lower. Warm extrusion enables the formation of a very dense compact (extruded product) having, for example, a relative density of 98% or more, further, 99% or more, and substantially 100%, depending on, for example, the material before extrusion and extrusion conditions.

[0148] A sealed product prepared by putting the material into a metal tube and sealing each end of the metal tube can be extruded. Such a sealed product can prevent a powder or the like from scattering, readily maintains the shape thereof, and is easily extruded. The metal tube that can be used is composed of a suitable metal that has workability with which extrusion working can be performed and strength with which the material put therein can be prevented from collapsing during extrusion. For example, the metal tube may be composed of pure aluminum, an aluminum alloy (for example, JIS standard, alloy number A1070, etc.), pure copper, or a copper alloy. After extrusion, the surface layer based on the metal tube may be removed or left. In the case where the surface layer is left, a covered Al alloy material having the surface layer as a covering layer, for example, a copper-covered Al alloy material is produced. The size of the metal tube may be selected in accordance with, for example, the amount and size of the material put in the metal tube and the thickness of the covering layer when the surface layer serves as the covering layer.

(Heat Treatment Step)

[0149] In this step, the above-described material (compact) is subjected to heat treatment to precipitate Fe mainly as a compound with Al and to adjust the size of the compound. In particular, since the heat treatment temperature is relatively low, the compound tends to become a very fine precipitate after heat treatment. Furthermore, since the heat treatment temperature is relatively low, the growth of crystal grains of the matrix is suppressed, and a very fine crystalline structure can be provided even after heat treatment. Specifically, an Al alloy material in which a very fine compound is dispersed in the fine crystalline structure, typically, an Al alloy material according to an embodiment having good elongation as well as high strength is produced.

[0150] The heat treatment conditions are determined such that the generation of cores of the compound containing Al and Fe is accelerated to cause the precipitation of the compound from the matrix to proceed, and the grain growth of the compound does not excessively occur. In particular, the heat treatment conditions are adjusted such that the average crystal grain size of the matrix satisfies 1,100 nm or less and the average major-axis length of the compound satisfies 100 nm or less.

[0151] The heat treatment temperature is 400° C. or lower. Typically, the heat treatment temperature may be higher than 350° C., or higher than a working temperature of warm forming when warm forming is performed. At a lower heat treatment temperature within the range that satisfies the conditions described above, coarsening of the compound and crystal grains tends to be suppressed. For example, the heat treatment temperature may be higher than 350° C. and 380° C. or lower.

[0152] The holding time may be, for example, about 0.1 hours or more and 6 hours or less, further, about 1 hour or more and 6 hours or less, and about 2 hours or more and 4 hours or less.

[0153] The heat treatment may be batch treatment or continuous treatment. The batch treatment is treatment in which an object to be heat-treated is enclosed in a heating vessel such as an atmosphere furnace, and heating is performed in this state. The continuous treatment is treatment in which an object to be heat-treated is continuously supplied and heated in a heating vessel, such as a belt furnace. In the continuous treatment, a parameter such as a speed of a belt may be adjusted so as to ensure a predetermined holding time.

[0154] The atmosphere in the heat treatment may be, for example, an air atmosphere or a low-oxygen atmosphere. The air atmosphere does not require atmosphere control and provides good heat treatment workability. The low-oxygen atmosphere is an atmosphere having a lower oxygen content than the atmosphere and can suppress the surface oxidation of the Al alloy material. The low-oxygen atmosphere may be, for example, a vacuum atmosphere (reduced-pressure atmosphere), an inert gas atmosphere, or a reducing gas atmosphere.

(Main Advantageous Effects)

[0155] The method for producing an Al alloy material according to an embodiment enables production of an Al alloy material having good elongation as well as high strength. From the viewpoints described below, the method for producing an Al alloy material according to an embodiment can produce an Al alloy material having good elongation as well as high strength with high productivity.

(v) In the forming process, a material having good formability is used, and thus a dense compact is satisfactorily formed. Therefore, the compact is produced with high productivity.

(w) The material provided for forming processing has good plastic deformability. Therefore, damage of a forming tool such as a forming die is reduced.

(x) Thermal energy necessary for warm forming and heat treatment tends to be relatively small.

(y) The compact before heat treatment has good cutting workability. Therefore, cutting work for forming a final shape is easily performed, and an Al alloy material having the final shape with high accuracy is easily produced.

(z) It is not necessary to perform forming such that the compact has open pores. In addition, the above-described impregnation step is unnecessary.

Test Example 1

[0156] Aluminum (Al) alloy materials having different Fe contents were produced under the various conditions

described in Tables 1 and 2. Tables 3 and 4 show structures and mechanical properties of the resulting Al alloy materials.

«Preparation of Sample»

(Sample Produced by Using Liquid Quenching Method)

[0157] Aluminum (Al) alloy materials of sample Nos. 1 to 25 shown in Table 1 are produced as described below.

<Preparation of Material>

[0158] Pure aluminum (purity 4N) and pure iron (purity 3N) are prepared as a raw material, and a melt of an Al-based alloy containing Fe and the balance of Al and incidental impurities is produced. The amount of pure iron added is adjusted such that the Al-based alloy has the Fe content (amount selected from a range of 2% by mass to 12% by mass, % by mass) shown in Table 1. A thin strip is produced by using the melt by a liquid quenching method, herein, a melt-spun method under the conditions described below.

[0159] More specifically, the raw material is melted by increasing the temperature to 1,000° C. in an argon atmosphere under reduced pressure (−0.02 MPa) to prepare a melt. The melt is sprayed onto a copper roll rotating at a surface peripheral speed of 50 m/s to produce a thin strip. The cooling rate of the melt is 80,000° C./s to 100,000° C./s (10,000° C./s). The thin strip has a width of about 2 mm. The thin strip has a thickness of about 30 μm. The thin strip has an unspecified length.

[0160] In sample Nos. 6 to 25, the thin strip is pulverized to form a powder, and this powder is used as a material provided for forming. In sample Nos. 1 to 5 described with “With rolling+pulverization” in the column “Forming condition” in Table 1, granules prepared by subjecting the thin strip to rolling followed by pulverization as described later are used as a material provided for forming.

[0161] The granules are prepared as follows. The thin strip is pulverized to form a powder. This powder is subjected to powder rolling described below and is then pulverized so as to have a particle size that is substantially equal to or less than the thickness of the rolled product. A rolling mill including a pair of rolls is used in the powder rolling. The rolls each have a diameter of 50 mmφ. The rolls each have a length of 80 mm. Regarding the rolling conditions, the pressing pressure is 5 tons, and the gap between the rolls is zero (zero gap). The rolled product has a thickness of about 0.5 mm to 1 mm. The rolled product is pulverized such that the powder diameter becomes 1 mm or less to provide the granules. The granules satisfy a flow rate of 20 seconds or less when the granules having a mass of 50 g fall freely through an orifice with a diameter of 4 mmφ.

[0162] According to the structural analysis of the resulting thin strip of each sample by XRD, a peak of a compound containing Al and Fe (mainly, $\text{Al}_{13}\text{Fe}_4$) was observed. The peak intensity of the compound is $\frac{1}{20}$ or less relative to the peak intensity of the aluminum phase. A cross section of the thin strip of each sample was observed with a scanning electron microscope (SEM) at a magnification ($\times 30,000$ in this case) at which the compound having a major-axis length of 5 nm or more can be observed. According to the results, no compound having a size of more than 100 nm was observed. These results show that the thin strip of each sample substantially has an Al single phase and has the

crystal structure of Al. It is also found that the use of an appropriate process such as a melt-spun method enables the production of a solid-solution product (thin strip in this case) in which Fe is not substantially precipitated but substantially the entire Fe is dissolved. The Fe content of the thin strip can be determined by, for example, infrared absorption spectrometry or inductively coupled plasma (ICP) optical emission spectroscopy.

<Forming Step>

[0163] In sample Nos. 1 to 5, a compact is produced by using the granules. In sample Nos. 6 to 25, a compact is produced by using the powder prepared by pulverizing the thin strip. Herein, press forming is performed such that the relative density becomes 85% or more in an argon atmosphere, at an applied pressure of 0.1 GPa, at a working temperature shown in Table 1 (temperature selected in the range of 150° C. to 400° C., ° C.), for a holding time of 30 minutes. A columnar compact having a diameter of 10 mmφ and a height of 3 mm is produced by this press forming. The case where the working temperature during forming is 150° C. corresponds to cold forming. The case where the working temperature during forming is 300° C. to 400° C. corresponds to warm forming.

<Heat Treatment Step>

[0164] The resulting compact of each sample is subjected to heat treatment. The heat treatment is batch treatment in a nitrogen atmosphere at a heating temperature of 375° C. ($\leq 400^\circ \text{C.}$) for a holding time of 60 minutes.

(Sample Produced by Using Gas Atomization Method)

[0165] Aluminum (Al) alloy materials of sample Nos. 26 to 45 shown in Table 2 are produced as described below.

[0166] A melt of an Al-based alloy containing Fe and the balance of Al and incidental impurities (where the Fe content is the amount shown in Table 2, % by mass) is produced as in sample No. 1, etc., and an atomized powder is produced by a gas atomization method. Known conditions are herein used, and the cooling rate of the melt is assumed to be 8,000° C./s or more and less than 10,000° C./s. The atomized powder has an average particle size of about 100 μm.

[0167] The atomized powder is used to produce a compact by press forming, and the compact is subjected to heat treatment. The conditions for the press forming are the same as those for sample Nos. 6 to 25, and the working temperature is the temperature (° C.) shown in Table 2. The heat treatment conditions are the same as those for sample No. 1, etc.

(Sample Produced by Mold Casting Method)

[0168] Aluminum (Al) alloy materials of sample Nos. 46 to 50 shown in Table 2 are wrought materials produced by subjecting a continuous cast product to heat treatment, the continuous cast product being produced by a known continuous casting method (mold casting method). More specifically, a melt of an Al-based alloy containing Fe and the balance of Al and incidental impurities (where the Fe content is the amount shown in Table 2, % by mass) is produced as in sample No. 1, etc., and a round bar-shaped continuous cast product having a diameter of 10 mmφ is produced by using a copper mold. This continuous cast

product is cut to have a length of 3 mm to prepare a columnar product having a diameter of 10 mm ϕ and a height of 3 mm. The columnar product is subjected to heat treatment. The heat treatment conditions are the same as those for sample No. 1, etc.

TABLE 1

Sample No.	Casting method	Fe content (% by mass)	Forming condition
1	Liquid quenching method	2	With rolling + pulverization Press forming at 150° C. (0.1 GPa)
2	Liquid quenching method	3	With rolling + pulverization Press forming at 150° C. (0.1 GPa)
3	Liquid quenching method	7.5	With rolling + pulverization Press forming at 150° C. (0.1 GPa)
4	Liquid quenching method	10	With rolling + pulverization Press forming at 150° C. (0.1 GPa)
5	Liquid quenching method	12	With rolling + pulverization Press forming at 150° C. (0.1 GPa)
6	Liquid quenching method	2	Press forming at 150° C. (0.1 GPa)
7	Liquid quenching method	3	Press forming at 150° C. (0.1 GPa)
8	Liquid quenching method	7.5	Press forming at 150° C. (0.1 GPa)
9	Liquid quenching method	10	Press forming at 150° C. (0.1 GPa)
10	Liquid quenching method	12	Press forming at 150° C. (0.1 GPa)
11	Liquid quenching method	2	Press forming at 300° C. (0.1 GPa)
12	Liquid quenching method	3	Press forming at 300° C. (0.1 GPa)
13	Liquid quenching method	7.5	Press forming at 300° C. (0.1 GPa)
14	Liquid quenching method	10	Press forming at 300° C. (0.1 GPa)
15	Liquid quenching method	12	Press forming at 300° C. (0.1 GPa)
16	Liquid quenching method	2	Press forming at 350° C. (0.1 GPa)
17	Liquid quenching method	3	Press forming at 350° C. (0.1 GPa)
18	Liquid quenching method	7.5	Press forming at 350° C. (0.1 GPa)
19	Liquid quenching method	10	Press forming at 350° C. (0.1 GPa)
20	Liquid quenching method	12	Press forming at 350° C. (0.1 GPa)
21	Liquid quenching method	2	Press forming at 400° C. (0.1 GPa)
22	Liquid quenching method	3	Press forming at 400° C. (0.1 GPa)
23	Liquid quenching method	7.5	Press forming at 400° C. (0.1 GPa)
24	Liquid quenching method	10	Press forming at 400° C. (0.1 GPa)
25	Liquid quenching method	12	Press forming at 400° C. (0.1 GPa)

TABLE 2

Sample No.	Casting method	Fe content (% by mass)	Forming condition
26	Gas atomization method	2	Press forming at 150° C. (0.1 GPa)
27	Gas atomization method	3	Press forming at 150° C. (0.1 GPa)

TABLE 2-continued

Sample No.	Casting method	Fe content (% by mass)	Forming condition
28	Gas atomization method	7.5	Press forming at 150° C. (0.1 GPa)
29	Gas atomization method	10	Press forming at 150° C. (0.1 GPa)
30	Gas atomization method	12	Press forming at 150° C. (0.1 GPa)
31	Gas atomization method	2	Press forming at 300° C. (0.1 GPa)
32	Gas atomization method	3	Press forming at 300° C. (0.1 GPa)
33	Gas atomization method	7.5	Press forming at 300° C. (0.1 GPa)
34	Gas atomization method	10	Press forming at 300° C. (0.1 GPa)
35	Gas atomization method	12	Press forming at 300° C. (0.1 GPa)
36	Gas atomization method	2	Press forming at 350° C. (0.1 GPa)
37	Gas atomization method	3	Press forming at 350° C. (0.1 GPa)
38	Gas atomization method	7.5	Press forming at 350° C. (0.1 GPa)
39	Gas atomization method	10	Press forming at 350° C. (0.1 GPa)
40	Gas atomization method	12	Press forming at 350° C. (0.1 GPa)
41	Gas atomization method	2	Press forming at 400° C. (0.1 GPa)
42	Gas atomization method	3	Press forming at 400° C. (0.1 GPa)
43	Gas atomization method	7.5	Press forming at 400° C. (0.1 GPa)
44	Gas atomization method	10	Press forming at 400° C. (0.1 GPa)
45	Gas atomization method	12	Press forming at 400° C. (0.1 GPa)
46	Mold casting method	2	—
47	Mold casting method	3	—
48	Mold casting method	7.5	—
49	Mold casting method	10	—
50	Mold casting method	12	—

«Structure and Relative Density of Compact»

[0169] For the compacts before heat treatment of sample Nos. 1 to 45 and the continuous cast products before heat treatment of sample Nos. 46 to 50, the relative density (%), the average crystal grain size (nm) of the matrix, the average major-axis length (nm) of precipitates, and the average number of precipitates (precipitates) are examined. Tables 3 and 4 show the results. Herein, the precipitate is a compound containing Al and Fe (herein, the compound is one in which the ratio of the number of atoms of Fe to Al is 0.1 or more, mainly, $\text{Al}_{13}\text{Fe}_4$). Regarding the items described in the column Compact (before heat treatment) in Table 4, sample Nos. 46 to 50 are described in terms of the continuous cast products before heat treatment.

[0170] Regarding sample Nos. 1 to 45, in extraction of a compact from the forming die of press forming, for compacts that could not be extracted so as to have the predetermined shape, the sample is described as “Shape could not be retained” in the column “Compact density” of Tables 3 and 4. Regarding such a sample whose shape could not be retained, the average crystal grain size of the matrix and the average major-axis length and the average number of precipitates are not measured. Regarding such a sample whose

shape could not be retained, the structure and mechanical properties of the heat-treated product described later are also not measured. In the description below, matters relating to compacts before heat treatment and heat-treated products are described except for the samples whose shape could not be retained, unless otherwise stated.

[0171] The relative density is determined by using the apparent density and the true density of the compact with $(\text{apparent density}/\text{true density}) \times 100$. The apparent density of the compact is determined by using the mass and the volume measured so as to include pores inside the compact. The true density of the compact is determined on the basis of the composition of the compact.

[0172] The average crystal grain size (nm) of the matrix is determined as follows.

[0173] A given cross section of the compact is observed with a SEM, and a measurement region of $5 \mu\text{m} \times 5 \mu\text{m}$ is chosen from a SEM image of the cross section. From a single cross section or a plurality of cross sections, a total of 30 or more measurement regions are chosen. All crystal grains present in each measurement region are extracted, a circle having an area equivalent to the cross-sectional area of each crystal grain is determined, and the diameter of the equivalent area circle, that is, the equivalent circle diameter is determined as a crystal grain size of the crystal grain. Among the extracted crystal grains, with respect to crystal grain size, crystal grains falling within the top 10% and crystal grains falling within the bottom 10% are excluded. Regarding the remaining 80% of the crystal grains, the average of the crystal grain size is determined. For example, if the number of extracted crystal grains is 30, a total of six crystal grains, namely, the top three crystal grains and the bottom three crystal grains, with respect to crystal grain size, are excluded, and the average of the crystal grain size is determined with respect to the remaining 24 crystal grains. The determined average value is defined as the average crystal grain size. The average crystal grain size is shown in Tables 3 and 4.

[0174] The extraction of the crystal grains and the extraction of the compound described later can be easily performed by subjecting a SEM image to image processing by using commercially available image processing software. A metallurgical microscope can also be used for observation of the cross section. The magnification of the microscope is adjusted within a range in which the size of the measurement object can be clearly measured. In observing the cross section, it is effective to perform grain boundary etching by performing treatment with a suitable solution and to prepare a SEM image having information about crystal orientation by using the electron backscattered diffraction (EBSD) technique.

[0175] The average major-axis length (nm) of the precipitates is determined as follows.

[0176] A given cross section of the compact is observed with a SEM, and a measurement region of $5 \mu\text{m} \times 5 \mu\text{m}$ is chosen from a SEM image of the cross section. From a single cross section or a plurality of cross sections, a total of 30 or more measurement regions are chosen. A maximum length of a compound containing Al and Fe and precipitated in each measurement region is measured. The maximum length of each compound is measured as follows.

[0177] As illustrated in FIG. 1, in the SEM image of the cross section, a particle 1 composed of a compound containing Al and Fe is sandwiched between two parallel lines

P1 and P2, and a gap between the parallel lines P1 and P2 is measured. The gap is the distance in a direction orthogonal to the parallel lines P1 and P2. A plurality of pairs of parallel lines P1 and P2 are chosen in any direction, and each of the gaps is measured. Among the plurality of gaps measured as described above, the maximum value is defined as a maximum length L1 of the particle 1.

[0178] Herein, among particles composed of the compound, particles having a maximum length of 5 nm or more are extracted. That is, particles having a maximum length of less than 5 nm are not extracted. The maximum length of each compound is defined as a major-axis length of the compound. Among the extracted compounds, with respect to major-axis length, particles falling within the top 10% and particles falling within the bottom 10% are excluded. Regarding the remaining 80% of the particles, the average of the major-axis length is determined. For example, if the number of extracted compounds is 30, a total of six compounds, namely, the top three compounds and the bottom three compounds, with respect to major-axis length, are excluded, and the average of the major-axis length is determined with respect to the remaining 24 compounds. The determined average value is defined as the average major-axis length. The average major-axis length is shown in Tables 3 and 4. Regarding a sample in which no compound having a maximum length of 5 nm or more is observed, "No precipitation" is described in the column "Precipitate, Size" and the column "Precipitate, Average number".

[0179] The average number of the precipitates (precipitates) is determined as follows.

[0180] A measurement region of $500 \text{ nm} \times 500 \text{ nm}$ (hereinafter, referred to as a precipitation measurement region) is chosen from a SEM image of the cross section of the compact. From a single cross section or a plurality of cross sections, a total of 30 or more precipitation measurement regions are chosen. Herein, one precipitation measurement region is chosen from each of the measurement regions of $5 \mu\text{m} \times 5 \mu\text{m}$ to thereby choose a total of 30 or more precipitation measurement regions. The number of compounds containing Al and Fe and present in each of the precipitation measurement regions, the compounds having a major-axis length of 5 nm or more and 100 nm or less, is measured. Among the numbers of compounds in the precipitation measurement regions, with respect to number, regions having a number of compounds falling within the top 10% and regions having a number of compounds falling within the bottom 10% are excluded. Regarding the remaining 80% of the regions, the average number of the compounds is determined. For example, if the number of the precipitation measurement regions is 30, a total of six regions, namely, the top three regions and the bottom three regions, with respect to number, are excluded, and the average number of compounds is determined with respect to the remaining 24 regions. The determined average value is defined as the average number. The average number is shown in Tables 3 and 4.

[0181] Structural analysis of the compacts of sample Nos. 1 to 25 is performed by XRD as in the thin strips. According to the results, although a peak of the compound is observed, the peak intensity of the compound is $1/15$ or less relative to the peak intensity of the aluminum phase. Specifically, in sample No. 1, No. 2, No. 6, and No. 7, the ratio of the peak intensity is $1/20$ or less. In the other samples, the ratio of the peak intensity is more than $1/20$ and $1/15$ or less. As shown in

Table 3, the average major-axis length of the compound is 100 nm or less, and the compound having a size of more than 100 nm is not observed. These results show that the compacts of sample Nos. 1 to 25 substantially have an Al single phase or have a phase close to an Al single phase.

«Structure and Mechanical Properties of Heat-Treated Product»

[0182] For the heat-treated product (Al alloy material) of each sample, the amount of Fe dissolved in the matrix (amount of Fe, % by mass), the average crystal grain size (nm) of the matrix, the average major-axis length (nm) of precipitates, the average number of precipitates (precipitates), the tensile strength (MPa), and the elongation at break (%) are examined. The results are shown in Tables 3 and 4.

[0183] The average crystal grain size of the matrix, and the average major-axis length and average number of the precipitates of the heat-treated product are determined as in the compact describe above.

[0184] The amount of dissolved Fe (% by mass) is herein determined by TEM-EDX.

[0185] Specifically, a cross section of the heat-treated product is observed with a TEM. The matrix is extracted from a TEM image of the cross section, and the Fe content in the matrix is measured. Ten or more measurement regions are chosen from one cross section. The Fe content is determined in each of the measurement regions, and the average value thereof is shown in Tables 3 and 4. In Table 4, “<0.1” means that the amount of dissolved Fe is less than 0.1% by mass.

[0186] The tensile strength (MPa) and the elongation at break (%) are measured in accordance with JIS Z 2241 (metallic material tensile testing method, 1998) with a general-purpose tensile tester. The measurement is performed at room temperature (for example, 25° C.).

TABLE 3

Sample No.	Compact (before heat treatment)				Heat-treated product					
	Compact density (relative density)	Crystal grain size (nm) Average crystal grain size	Precipitate Size (nm) Average major-axis length	Precipitate number Average number (500 nm sq.)	Amount of Fe in matrix (% by mass)	Crystal grain size (nm) Average crystal grain size	Precipitate Size (nm) Average major-axis length	Precipitate number Average number (500 nm sq.)	Tensile strength (MPa)	Elongation at break (%)
1	96%	350	No precipitation	No precipitation	0.3	410	19	55	210	4.1
2	95%	370	No precipitation	No precipitation	0.3	430	17	130	335	3
3	94%	380	13.5	15	0.4	455	22	162	390	2.4
4	93%	360	15	11	0.4	440	24	171	430	2.1
5	84%	530	18	7	0.4	630	25	190	345	0.6
6	86%	330	No precipitation	No precipitation	0.3	390	12.5	160	220	0.7
7	81%	350	No precipitation	No precipitation	0.3	395	14	224	215	0.5
8	Shape could not be retained	—	—	—	—	—	—	—	—	—
9	Shape could not be retained	—	—	—	—	—	—	—	—	—
10	Shape could not be retained	—	—	—	—	—	—	—	—	—
11	89%	450	14.5	45	0.3	530	17	86	220	4.3
12	85%	440	15	40	0.3	550	16	158	250	1.8
13	83%	470	14	50	0.4	550	20	220	225	0.7
14	Shape could not be retained	—	—	—	—	—	—	—	—	—
15	Shape could not be retained	—	—	—	—	—	—	—	—	—
16	96%	540	16	83	0.2	580	19	29	250	6.2
17	94%	530	16.5	76	0.2	570	22	80	315	3.5
18	90%	540	17	68	0.3	580	30	141	350	2.7
19	86%	580	17	70	0.3	600	33.5	170	390	2.2
20	82%	760	17.5	64	0.4	830	60	24	365	0.6
21	98%	890	84	3	0.1	1050	90	3	165	8.3
22	97%	920	88	4	0.2	1170	95	4	180	4.3
23	95%	930	90	8	0.2	1090	95	12	255	3.3
24	93%	980	93	9	0.2	1085	100	11	275	2.5
25	92%	1060	98	10	0.2	1320	110	9	245	0.8

TABLE 4

Sample No.	Compact (before heat treatment)					Heat-treated product				
	Compact density (relative density)	Crystal grain size (nm) Average crystal grain size	Precipitate Size (nm) Average major-axis length	Precipitate Average number (500 nm sq.)	Amount of Fe in matrix (% by mass)	Crystal grain size (nm) Average crystal grain size	Precipitate Size (nm) Average major-axis length	Precipitate Average number (500 nm sq.)	Tensile strength (MPa)	Elongation at break (%)
26	Shape could not be retained	—	—	—	—	—	—	—	—	—
27	Shape could not be retained	—	—	—	—	—	—	—	—	—
28	Shape could not be retained	—	—	—	—	—	—	—	—	—
29	Shape could not be retained	—	—	—	—	—	—	—	—	—
30	Shape could not be retained	—	—	—	—	—	—	—	—	—
31	83%	2150	360	0.4	0.1	2750	510	0.33	180	2.8
32	Shape could not be retained	—	—	—	—	—	—	—	—	—
33	Shape could not be retained	—	—	—	—	—	—	—	—	—
34	Shape could not be retained	—	—	—	—	—	—	—	—	—
35	Shape could not be retained	—	—	—	—	—	—	—	—	—
36	91%	1030	275	0.8	0.1	1100	290	0.75	200	5.6
37	87%	1100	290	0.8	0.1	1180	320	0.75	245	2.2
38	88%	1210	335	0.8	0.1	1300	360	0.66	290	0.9
39	Shape could not be retained	—	—	—	—	—	—	—	—	—
40	Shape could not be retained	—	—	—	—	—	—	—	—	—
41	94%	3100	430	0.4	<0.1	3200	660	0.33	185	6.8
42	93%	3150	440	0.4	<0.1	3260	650	0.33	200	2.6
43	93%	3100	425	0.4	0.1	3300	640	0.30	245	1.5
44	91%	3350	505	0.4	0.1	3450	730	0.30	250	0.8
45	88%	3630	680	0.3	0.1	3860	860	0.25	220	0.4
46	98%	8800	630	0.7	<0.1	9600	690	0.50	210	5.3
47	98%	9050	680	0.7	<0.1	9530	720	0.50	230	1.9
48	98%	10200	850	0.5	<0.1	10500	860	0.40	230	0.6
49	98%	11000	1030	0.5	<0.1	11500	1040	0.33	210	0.4
50	97%	13200	1450	0.3	<0.1	13800	1470	0.25	220	0.5

[0187] Tables 3 and 4 show the following.

<With Regard to Compact>

[0188] (1) The use of the materials prepared by the liquid quenching method provides dense compacts having a relative density of 85% or more even at a relatively low working temperature of 350° C. or lower during forming, compared with the case of using the gas atomized powders. This is proved by the comparison between sample Nos. 1 to 20 and sample Nos. 26 to 40. In sample Nos. 1 to 20, which are prepared by using the materials described above, the number of samples whose shape could not be retained is small, and a large number of the samples have a relative density of 85% or more, compared with sample Nos. 26 to 40, which are prepared by using the gas atomized powders. The results also show that at a cooling rate of the melt of 10,000° C./s or more, a material having good formability is obtained compared with the case where the cooling rate of the melt is less than 10,000° C./s.

(2) At a working temperature of 400° C. during forming, dense compacts having a relative density of 85% or more are

obtained from both the materials and the gas atomized powders (refer to, sample Nos. 21 to 25 and sample Nos. 41 to 45).

(3) The compacts obtained by using the materials prepared by the liquid quenching method have very fine crystal grains compared with the compacts obtained by using the gas atomized powders. In addition, compounds containing Al and Fe are not substantially precipitated. Alternatively, even when compounds containing Al and Fe are precipitated, the compounds have a very short average major-axis length and are present in a dispersed manner.

[0189] More specifically, in the compacts of sample Nos. 26 to 45 obtained by using the gas atomized powders, the average crystal grain size of the matrix is 1,030 nm or more, 2,000 nm or more, and further, 3,000 nm or more in many samples. The average major-axis length of the compounds is 275 nm or more, 300 nm or more, and further, 400 nm or more in many samples. The average number of the compounds is less than 1 in the precipitation measurement region, and the number of very fine compounds having an average major-axis length of 100 nm or less is extremely small. These results show that, in the compacts of sample Nos. 26 to 45, very coarse compounds having an average

major-axis length of about 300 nm or more are locally precipitated in a coarse crystalline structure having an average crystal grain size of about 2,000 nm or more.

[0190] In contrast, in the compacts of sample Nos. 1 to 25 obtained by the liquid quenching method, the average crystal grain size of the matrix is 1,100 nm or less, 800 nm or less, and further, 600 nm or less in many samples. The average major-axis length of the compounds containing Al and Fe is 100 nm or less, and 35 nm or less in many samples. The average number of the compounds is several or more and about 85 or less in the precipitation measurement region. These results show that, in the compacts of sample Nos. 1 to 25, in a very fine crystalline structure having an average crystal grain size of about 1,100 nm or less, the compounds are not substantially precipitated or very fine compounds having an average major-axis length of 100 nm or less are present in a dispersed manner even if the compounds are precipitated.

(4) In the continuous cast products of sample Nos. 46 to 50, both the crystal grains and the compounds are larger than those of the compacts of sample Nos. 26 to 45 obtained by using the gas atomized powders. The average number of the compounds is less than 1 in the precipitation measurement region, and the number of very fine compounds having an average major-axis length of 100 nm or less is extremely small. Quantitatively, in the continuous cast products, extremely coarse compounds having an average major-axis length of 630 nm or more are locally precipitated in an extremely coarse crystalline structure including a matrix having an average crystal grain size of about 9,000 nm or more.

<With Regard to Heat-Treated Product (Al Alloy Material)>

[0191] (1) When the compacts of sample Nos. 1 to 25 obtained by using the materials prepared by the liquid quenching method are subjected to heat treatment at 400° C. or lower, the crystal grains and the compounds containing Al and Fe become larger than those of the structure before the heat treatment. Alternatively, the compounds are precipitated, and the average number of compounds having an average major-axis length of 100 nm or less is large. Quantitatively, in many samples among the heat-treated products of sample Nos. 1 to 25, very fine compounds having an average major-axis length of 100 nm or less are present in a dispersed manner in a very fine crystalline structure including a matrix having an average crystal grain size of 1,100 nm or less. The aluminum phase, which mainly constitutes the matrix, mainly has the fcc structure.

(2) Among the heat-treated products of sample Nos. 1 to 25, samples which are dense and in which very fine compounds having an average major-axis length of 100 nm or less are present in a dispersed manner in a very fine crystalline structure including a matrix having an average crystal grain size of 1,100 nm or less have high tensile strength and high elongation at break. More specifically, the heat-treated products of sample Nos. 2 to 4, No. 12, Nos. 17 to 19, No. 23, and No. 24 (hereinafter, these samples may be collectively referred to as heat-treated products of sample No. 2, etc.) have a relative density of 85% or more. Many of these samples have a relative density of 90% or more. Furthermore, the heat-treated products of sample No. 2, etc. have a tensile strength of 250 MPa or more and an elongation at break of 1% or more. Many of these samples have a tensile strength of 255 MPa or more and an elongation at break of

2% or more and thus have high tensile strength and high elongation at break in a balanced manner.

(3) Among the heat-treated products of sample Nos. 1 to 25, samples having an Fe content of 2% by mass have a high relative density, include a matrix having an average crystal grain size of 1,100 nm or less, and include the compounds having an average major-axis length of 100 nm or less, however, the tensile strength of the samples tends to be low. In this test, a tensile strength exceeding 250 MPa is not achieved at an Fe content of 2% by mass. At an Fe content of 12% by mass, the relative density may be less than 85%, the shape may not be retained, the average major-axis length of the compounds may exceed 100 nm, and the elongation at break is low. In view of this, the Fe content is preferably more than 2% by mass and less than 12% by mass.

(4) In the heat-treated products of sample Nos. 26 to 45 obtained by using the gas atomized powders and the heat-treated products of sample Nos. 46 to 50, which are wrought materials, the crystal grains and the compounds are larger than and the average number of compounds having an average major-axis length of 100 nm or less is smaller than those of the structures before the heat treatment. Quantitatively, in these heat-treated products, coarse compounds having an average major-axis length of about 300 nm or more are locally present in a coarser crystalline structure including a matrix having an average crystal grain size of 1,100 nm or more, further, about 3,000 nm or more. The presence of such coarse crystal grains and coarse compounds decreases at least one of the tensile strength and the elongation at break, resulting in poor balance between the tensile strength and the elongation at break.

[0192] The heat-treated product of each sample substantially maintains the relative density of the compact.

<Heat-Treated Products of Sample No. 2, Etc.>

[0193] The heat-treated products of sample Nos. 2 to 4, No. 12, Nos. 17 to 19, No. 23, and No. 24, which have good elongation as well as high strength, will now be focused on.

(1) Regarding the heat-treated products of sample No. 2, etc. and the wrought materials (heat-treated products) of sample Nos. 47 to 49, samples having the same Fe content are compared. An amount of increase in tensile strength relative to the tensile strength of the corresponding wrought material is 8.5% or more. In addition, the elongation at break is 1% or more, further, 1.5% or more. Accordingly, the heat-treated products of sample No. 2, etc. have higher strength and better elongation than the wrought materials.

[0194] In particular, among the heat-treated products of sample No. 2, etc., samples other than sample No. 12 have an amount of increase in the tensile strength of 10% or more and thus have better strength than the wrought materials. In sample Nos. 2 to 4 and Nos. 17 to 19, the amount of increase in the tensile strength is 30% or more. Sample Nos. 2 to 4 and Nos. 17 to 19 have a high elongation at break of 2% or more while having a high tensile strength of 300 MPa or more, and thus have good elongation as well as better strength. One possible reason for this is that very fine compounds tend to be uniformly dispersed in a very fine crystalline structure due to the following (α) and (β).

(α) The average crystal grain size of the matrix is smaller, namely, 600 nm or less, and the major-axis length of the compounds containing Al and Fe is smaller, namely, 35 nm or less.

(β) The amount of Fe dissolved in the matrix is very small, namely, 0.5% by mass or less. In addition, the average number of precipitates having an average major-axis length of 100 nm or less is 10 or more, further, 80 or more and 175 or less. In many samples, the average number of precipitates is 115 or more and 175 or less. That is, the contained Fe is mainly present as a very fine compound in an isolated state.

[0195] Regarding the heat-treated products of sample Nos. 2 to 4 and Nos. 17 to 19, samples having the same Fe content are compared. The heat-treated products of sample Nos. 2 to 4 have higher tensile strength than heat treatment of Nos. 17 to 19. One possible reason for this is as follows. The heat-treated products of sample Nos. 2 to 4 have a smaller average crystal grain size of the matrix and a shorter average major-axis length of the compounds than Nos. 17 to 19. In addition, the average number of the very fine compounds is large, and thus the strength-improving effect due to grain boundary strengthening of crystal grains and dispersion strengthening of the compounds is easily obtained. One possible reason why the difference in structure of the heat-treated product occurred is the difference in production conditions. The heat-treated products of sample Nos. 2 to 4 are produced by further rolling a powder or the like prepared by rapid cooling of the melt, pulverizing the resulting rolled product, and then subjecting the pulverized product to cold forming. In contrast, the heat-treated products of sample Nos. 17 to 19 are produced by subjecting the powder or the like to warm forming. It is assumed that the cold forming suppressed the growth of the crystal grains and compounds.

(2) In the heat-treated products of sample No. 2, etc., with an increase in the Fe content, the tensile strength tends to be high, and with a decrease in the Fe content, the elongation at break tends to be high. One possible reason for the improvement in strength is as follows. With an increase in the Fe content, the average number of very fine precipitates increases, and the strength-improving effect due to dispersion strengthening of the compounds is more easily obtained. Furthermore, the fine precipitates (the compounds described above) also easily suppress the growth of crystal grains, and the crystal grains are very fine. Thus, the strength-improving effect due to grain boundary strengthening is also easily obtained. One possible reason for the improvement in elongation at break is as follows. With a decrease in the Fe content, the precipitates tend to be small, and the average number of the precipitates also decreases. Thus, it is easy to suppress the situation where the precipitates serve as starting points of cracking.

[0196] Accordingly, an Al alloy material containing 3% by mass or more and 10% by mass or less of Fe and having good elongation as well as high strength was shown. It was also shown that this Al alloy material is dense (has a relative density of 85% or more, preferably 90% or more), the matrix has a very fine crystalline structure (has an average crystal grain size of 1,100 nm or less), Fe is present mainly as a compound, and this compound is very fine (the average major-axis length of the compound is 100 nm or less) and is present in the crystalline structure in a dispersed manner. Furthermore, it was also shown that such an Al alloy material can be produced by producing a dense compact (having a relative density of 85% or more) by using a powder or the like produced through rapid cooling of a melt, and subjecting the compact to heat treatment at 400° C. or lower. Thus, this Al alloy material can be easily produced by

a production method equivalent to a powder metallurgy process and has high productivity.

[0197] In addition, it was shown that the powder or the like produced by rapid cooling of a melt does not substantially contain a precipitate of Fe, has good formability, and thus satisfactorily provides a dense compact having a relative density of 85% or more, further, 90% or more, even when the working temperature during forming is a relatively low temperature of 400° C. or lower. With an increase in the working temperature during forming in a range of 400° C. or lower, the relative density tends to increase, and the strength tends to increase (refer to and compare between sample No. 12 and sample No. 17). It was shown that the powder or the like obtained by further rolling a solid-solution product prepared by rapid cooling of a melt, and then pulverizing the rolled product has better formability, and a dense compact having a relative density of 90% or more is satisfactorily obtained even by cold forming at a working temperature during forming of 150° C. or lower.

[0198] It was also shown that when the heat treatment temperature is a relatively low temperature of 400° C. or lower, the crystal grains of the matrix can be made very fine while the above-described compounds can be made very fine after the heat treatment. It was shown that when the pulverized product of the rolled product is subjected to cold forming, the crystal grains and the compounds can be made small, and the average number of very fine compounds can be increased, compared with the case where the powder or the like prepared by rapid cooling of a melt is provided for warm forming.

[0199] The present invention is not limited to the examples described above but is defined by the appended claims. The present invention is intended to encompass all modifications within meanings and scopes equivalent to the claims.

[0200] For example, the Fe content, production conditions (for example, the cooling rate of the melt, the working temperature and pressure to be applied during forming, and heat treatment conditions), and the shape and dimensions of the Al alloy material may be appropriately changed in Test Example 1.

REFERENCE SIGNS LIST

- [0201]** 1 particle composed of compound
 - [0202]** P1, P2 parallel line
 - [0203]** L1 maximum length (major-axis length)
 - [0204]** L2 minor-axis length
1. An aluminum alloy material comprising:
 - a composition containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities; and
 - a structure including a matrix and a compound, wherein the matrix is composed mainly of Al, the compound contains Al and Fe, a relative density is 85% or more, and in any cross section, the matrix has an average crystal grain size of 1,100 nm or less, and the compound has an average major-axis length of 100 nm or less.
 2. The aluminum alloy material according to claim 1, wherein the average crystal grain size is 600 nm or less, and the average major-axis length is 35 nm or less.
 3. The aluminum alloy material according to claim 1, wherein when a plurality of square measurement regions each having a side length of 500 nm are chosen in the cross

section, an average number of the compounds having a major-axis length of 5 nm or more and 100 nm or less in the measurement regions is 10 or more.

4. The aluminum alloy material according to claim 3, wherein the average number is 80 or more and 175 or less.

5. The aluminum alloy material according to claim 1, having a tensile strength of 300 MPa or more.

6. The aluminum alloy material according to claim 5, having an elongation at break of 1% or more.

7. A method for producing an aluminum alloy material, comprising:

a step of rapidly cooling a melt of an aluminum alloy containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities to produce a powdery or flaky material in which the Fe is dissolved;

a step of subjecting the material to warm forming at a temperature of 400° C. or lower to form a dense body having a relative density of 85% or more; and

a step of subjecting the dense body to heat treatment at a temperature of 400° C. or lower.

8. A method for producing an aluminum alloy material, comprising:

a step of rapidly cooling a melt of an aluminum alloy containing 3% by mass or more and 10% by mass or less of Fe and the balance of Al and incidental impurities to produce a powdery or flaky material in which the Fe is dissolved;

a step of subjecting the material to cold forming to form a dense body having a relative density of 85% or more; and

a step of subjecting the dense body to heat treatment at a temperature of 400° C. or lower.

9. The method for producing an aluminum alloy material according to claim 7, wherein, in X-ray diffraction of the dense body, a peak intensity of a compound containing Al and Fe is $\frac{1}{10}$ or less relative to a peak intensity of an aluminum phase.

10. The method for producing an aluminum alloy material according to claim 8, wherein, in X-ray diffraction of the dense body, a peak intensity of a compound containing Al and Fe is $\frac{1}{10}$ or less relative to a peak intensity of an aluminum phase.

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