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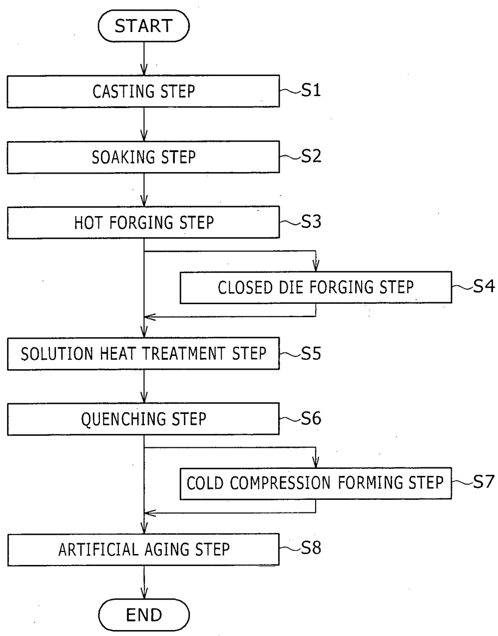
(54) ALUMINIUM ALLOY FORGING AND METHOD FOR PRODUCING THE SAME

(57) Disclosed is an aluminum alloy forging having excellent high-temperature properties (e.g., fatigue strength in a high-temperature environment). The aluminum alloy forging is formed by forging an aluminum alloy. The aluminum alloy contains Cu in a content of 3.0 to 8.0 mass percent, Mg in a content of 0.01 to 2.0 mass percent, Ag in a content of 0.05 to 1.0 mass percent, and Mn in a content of 0.05 to 1.5 mass percent, with the remainder being Al and inevitable impurities. The aluminum forging has an average grain size of 500 μm or less and a grain aspect ratio (length-to-width ratio) of 10 or less.

FIG. 1



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Description

FIELD OF INVENTION

[0001] The present invention relates to an aluminum alloy forging for a high-speed movable part that is configured to rotate or slide at a high speed; and a method for producing the aluminum alloy forging.

BACKGROUND OF INVENTION

[0002] Aluminum characteristically has a low density and high strengths and is easy to work. Taking full advantage of these characteristics, aluminum alloy forgings are used in applications that require a light weight, satisfactory strength, and satisfactory working properties. Such applications are exemplified by transport machinery such as railroad vehicles, automobiles, and ships; and a variety of machinery parts and engine parts. Specifically, the aluminum alloy forgings are used in high-speed movable parts that are configured to rotate or slide at high speed, such as spinning rotors (small-sized vanes) and rotary impellers (large-sized vanes) typically of generators and compressors, and engine pistons.

[0003] The high-speed movable parts for use in these applications are used in a high-temperature environment of higher than 100°C, are configured to rotate and/or to slide, and thereby require high-temperature properties (heat resistance and high-temperature yield strength). Techniques relating to aluminum alloys and aluminum alloy forgings as developed to meet the requirements are disclosed typically in Japanese Patent No. 4088546, Japanese Patent No. 4058398, Japanese Patent No. 3997009, Japanese Patent No. 4676906, Japanese Unexamined Patent Application Publication (JP-A) No. 2013-142168, and JP-A No. 2013-14835.

[0004] Japanese Patent No. 4088546 discloses a method for producing an aluminum alloy forging having excellent high-temperature properties. The aluminum alloy forging contains Cu in a content of 4.0 to 7.0 mass percent, Mg in a content of 0.2 to 0.4 mass percent, and Ag in a content of 0.05 to 0.7 mass percent, with the remainder including aluminum and inevitable impurities. According to the method, an ingot having the chemical composition is soaked at a temperature of 500°C to 545°C, hot-forged at a temperature of 280°C to 360°C, and subjected sequentially to solution heat treatment at a temperature of 510°C to 545°C, quenching, and artificial aging to give the aluminum alloy forging. The resulting aluminum alloy forging has a yield strength of 400 MPa or more at room temperature.

[0005] Japanese Patent No. 4058398 discloses an aluminum alloy forging having excellent high-temperature fatigue strength. The aluminum alloy forging contains Cu in a content of 4.0 to 7.0 mass percent, Mg in a content of 0.2 to 0.4 mass percent, Ag in a content of 0.05 to 0.7 mass percent, and V in a content of 0.05 to 0.15 mass percent with the remainder including aluminum and inevitable impurities. The distribution density (number density) of Al-V precipitates in the forging microstructure is 1.5 or more per cubic micrometer.

[0006] Japanese Patent No. 3997009 discloses an aluminum alloy cold-forging for high-speed movable parts. The aluminum alloy cold-forging contains Cu in a content of 1.5 to 7.0 mass percent and Mg in a content of 0.01 to 2.0 mass percent with the remainder including aluminum and inevitable impurities. The aluminum alloy cold-forging has a microstructure including the θ' phase and/or the Ω phase and including equiaxed recrystallized grains each having a grain size of 500 μm or less. The area percentage of fine recrystallized grains in the microstructure including the equiaxed recrystallized grains is 10% or less, where the fine recrystallized grains each have a grain size of 1 μm or less and unite with each other to form an aggregate (assembly). The aluminum alloy cold-forging has a 1000-hr creep rupture strength of 250 N/mm^2 or more and a high-temperature yield strength of 280 N/mm^2 or more.

[0007] Japanese Patent No. 4676906 discloses a malleable heat-resistant aluminum alloy. The aluminum alloy contains Cu in a content of 5.1% to 6.5% (in mass percent, hereinafter the same), Mg in a content of 0.10% to 0.7%, Ag in a content of 0.10% to 1.0%, Mn in a content of 0.10% to 0.50%, and Ti in a content of 0.22% to 0.50%, where the ratio Mn/Ti of the Mn content to the Ti content is from 0.5 to 2.5, with the remainder including Al and inevitable impurities.

[0008] JP-A No. 2013-142168 discloses an aluminum alloy forging having excellent heat resistance. The aluminum alloy forging is formed by forging an aluminum alloy containing Cu in a content of 5.1% to 6.5% (in mass percent, hereinafter the same), Mg in a content of 0.30% to 0.70%, Ag in a content of 0.10% to 1.0%, Mn in a content of 0.10% to 0.50%, Cr in a content of 0.07% to 0.11%, and Ti in a content of 0.06% to 0.30%, with the remainder including Al and inevitable impurities. The aluminum alloy forging has a creep rupture life of 500 hours or longer at 200°C and 160 MPa.

[0009] JP-A No. 2013-14835 discloses an aluminum alloy having excellent high-temperature properties. The aluminum alloy contains Si in a content of greater than 0.1 mass percent to 1.0 mass percent, Cu in a content of 3.0 mass percent to 7.0 mass percent, Mn in a content of 0.05 mass percent to 1.5 mass percent, Mg in a content of 0.01 mass percent to 2.0 mass percent, Ti in a content of 0.01 mass percent to 0.10 mass percent, and Ag in a content of 0.05 mass percent to 1.0 mass percent, where Zr is controlled in a content of less than 0.1 mass percent, with the remainder including Al and inevitable impurities.

SUMMARY OF INVENTION

[0010] High-speed movable parts such as spinning rotors and rotary impellers should have higher stability and better material properties in a high-temperature environment. The techniques disclosed in Japanese Patent No. 4088546, Japanese Patent No. 3997009, Japanese Patent No. 4676906, JP-A No. 2013-142168, and JP-A No. 2013-14835 can meet the requirements, but fail to consider improvements in fatigue strength in a high-temperature environment at all. Disadvantageously, the techniques disclosed in the literature fail to realize an aluminum alloy forging that has higher fatigue strength in a high-temperature environment.

[0011] The aluminum alloy forging according to the technique disclosed in Japanese Patent No. 4058398 contains vanadium (V) as an essential component, allows special precipitates, i.e., Al-V precipitates to precipitate in a specific distribution density, and thereby has higher fatigue strength in a high-temperature environment. However, further higher fatigue strength in a high-temperature environment is required.

[0012] The present invention has been made under these circumstances and has an object to provide an aluminum alloy forging having excellent high-temperature properties (fatigue strength in a high-temperature environment). The present invention has another object to provide a method for producing the aluminum alloy forging.

[0013] The present invention has achieved the objects and provides, in one embodiment, an aluminum alloy forging formed by forging an aluminum alloy. The aluminum alloy contains Cu in a content of 3.0 to 8.0 mass percent, Mg in a content of 0.01 to 2.0 mass percent, Ag in a content of 0.05 to 1.0 mass percent, and Mn in a content of 0.05 to 1.5 mass percent, with the remainder including Al and inevitable impurities. The aluminum alloy forging has an average grain size of 500 μm or less and a grain aspect ratio (length-to-width ratio) of 10 or less.

[0014] The aluminum alloy constituting the aluminum alloy forging according to the embodiment of the present invention may further contain at least one element selected from the group consisting of Zn in a content of 0.01 to 0.40 mass percent, Si in a content of 0.01 to 1.00 mass percent, V in a content of 0.01 to 0.15 mass percent, Cr in a content of 0.01 to 0.30 mass percent, Zr in a content of 0.01 to 0.50 mass percent, Sc in a content of 0.01 to 1.00 mass percent, and Ti in a content of 0.01 to 0.20 mass percent.

[0015] The present invention also provides, in another embodiment, a method for producing an aluminum alloy forging. The method includes the steps of casting, soaking, hot forging, solution heat treatment, quenching, and artificial aging. Specifically, an aluminum alloy having the chemical composition is melt and cast to give an ingot (casting step). The ingot is soaked at a holding temperature of 500°C to 545°C (soaking step). The ingot after the soaking is hot-forged at a temperature of 180°C to 360°C at a forging ratio of 1.5 or more to give a forging (hot forging step). The forging after the hot forging is subjected to solution heat treatment at a holding temperature of 510°C to 545°C (solution heat treatment step). The forging after the solution heat treatment is quenched at an average cooling rate in the temperature range of 400°C to 290°C of 10°C/min. to less than 30000°C/min. (quenching step). The forging after the quenching is subjected to artificial aging (artificial aging step).

[0016] In the method for producing an aluminum alloy forging according to the embodiment of the present invention, the hot forging step preferably includes performing forging of the ingot sequentially in at least two different directions.

[0017] In the method for producing an aluminum alloy forging according to the embodiment of the present invention, the hot forging step preferably includes performing forging of the ingot in three different directions.

[0018] In the method for producing an aluminum alloy forging according to the embodiment of the present invention, the forging is preferably performed at a temperature of from 180°C to lower than 280°C.

[0019] The method for producing an aluminum alloy forging according to the embodiment of the present invention may further include a closed-die forging step between the hot forging step and the solution heat treatment step. In the closed-die forging step, the forging is forged in closed dies at a temperature of 180°C to 360°C.

[0020] In the method for producing an aluminum alloy forging according to the embodiment of the present invention, the closed-die forging is preferably performed at a temperature of from 180°C to lower than 280°C.

[0021] The aluminum alloy forging according to the embodiment of the present invention has excellent high-temperature properties (fatigue strength in a high-temperature environment). The method for producing an aluminum alloy forging according to the embodiment of the present invention can produce an aluminum alloy forging having excellent high-temperature properties (fatigue strength in a high-temperature environment).

BRIEF DESCRIPTION OF DRAWINGS

[0022]

FIG. 1 is a flow chart illustrating individual steps of a method for producing an aluminum alloy forging according to an embodiment of the present invention;

FIG. 2 is an explanatory drawing illustrating how to determine the average grain size and the grain aspect ratio (length-to-width ratio); and

FIG. 3 is an explanatory drawing illustrating how to determine the average grain size and the grain aspect ratio (length-to-width ratio).

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0023] Embodiments of the aluminum alloy forging and the production method of the aluminum alloy forging according to the present invention will be illustrated in detail with reference to the attached drawings as appropriate.

Aluminum Alloy Forging

[0024] An aluminum alloy forging (hereinafter briefly referred to as "aluminum forging") according to one embodiment of the present invention is formed by forging an aluminum alloy containing Cu in a content of 3.0 to 8.0 mass percent, Mg in a content of 0.01 to 2.0 mass percent, Ag in a content of 0.05 to 1.0 mass percent, and Mn in a content of 0.05 to 1.5 mass percent, with the remainder including Al and inevitable impurities. The aluminum forging according to the embodiment has an average grain size of 500 μm or less and a grain aspect ratio (length-to-width ratio) of 10 or less.

[0025] The aluminum forging corresponds to an particle prepared sequentially through, after the completion of the after mentioned hot forging step S3, the steps from the solution heat treatment step S5 to the artificial aging step S8 (see FIG. 1); and an article prepared sequentially through, after the completion of the hot forging step S3, the closed-die forging step S4, and the steps from the solution heat treatment step S5 to the artificial aging step S8 (also see FIG. 1). A cold compression forming step S7 may be optionally performed in any case, as described later. Although also affected by the chemical composition, the average grain size and grain aspect ratio of the aluminum forging according to the embodiment of the present invention are approximately determined by how the strain state is in the material, where the strain is given by or affected by forging conditions in the hot forging step S3 and the closed-die forging step S4 (when performed). The solution heat treatment step S5 allows the strain state to appear as the shape (dimensions) of microstructure, namely, as the average grain size and grain aspect ratio. The average grain size and grain aspect ratio appeared by the solution heat treatment step S5 change little, and effects obtained by the appeared average grain size and grain aspect ratio also change little as a result of downstream treatment(s). Accordingly, the average grain size and grain aspect ratio can also be determined by measurement even after the quenching step S6 or the artificial aging step S8 performed after the solution heat treatment step S5.

[0026] The aluminum alloy constituting the aluminum forging according to the embodiment may further contain at least one element selected from the group consisting of Zn in a content of 0.01 to 0.40 mass percent, Si in a content of 0.01 to 1.00 mass percent, V in a content of 0.01 to 0.15 mass percent, Cr in a content of 0.01 to 0.30 mass percent, Zr in a content of 0.01 to 0.50 mass percent, Sc in a content of 0.01 to 1.00 mass percent, and Ti in a content of 0.01 to 0.20 mass percent. The alloy chemical composition and grain dimensions and properties will be described below individually.

Alloy Chemical Composition

Copper (Cu)

[0027] Copper (Cu) is a basic composition of the aluminum forging according to the embodiment. Cu offers both solute strengthening and precipitation strengthening and allows the aluminum forging to have higher levels of creep properties in a room-temperature environment, creep properties in a high-temperature environment, and high-temperature yield strength (fatigue strength in a high-temperature environment). More specifically, Cu allows the θ' phase and/or Ω phase to precipitate finely and densely in the (100) plane and/or the (111) plane of the aluminum alloy upon artificial aging performed at a high temperature and allows the aluminum forging after the artificial aging to have higher strengths. Cu exhibits this effect when present in a content of 3.0 mass percent or more, and more preferably 4.0 mass percent or more. Cu, if present in a content less than 3.0 mass percent, may exhibit the effect insufficiently and may fail to allow the aluminum forging to have sufficient creep properties in a room-temperature environment and in a high-temperature environment and a sufficient high-temperature yield strength. In contrast, Cu, if present in a content greater than 8.0 mass percent, may cause the aluminum forging to have inferior forgeability due to excessively high strengths. To prevent these, the Cu content may be controlled to 3.0 to 8.0 mass percent, preferably 4.0 to 7.0 mass percent, and more preferably 4.5 to 7.0 mass percent. As used herein the term "room temperature" refers to a temperature around ambient (room) temperature, specifically, a temperature of about 25°C; and the term "high temperature" refers to a temperature of about 100°C or higher.

Magnesium (Mg)

[0028] Magnesium (Mg) offers both solute strengthening and precipitation strengthening and mainly allows the aluminum forging to have higher levels of creep properties in a high-temperature environment, room-temperature yield strength, and high-temperature yield strength, as with Cu. More specifically, Mg allows the θ' phase and/or Ω phase to precipitate finely and densely in the (100) plane and/or the (111) plane of the aluminum alloy upon artificial aging performed at a high temperature and allows the aluminum forging after the artificial aging to have higher strengths, as with Cu. Mg exhibits this effect when present in a content of 0.01 mass percent or more. Mg, if present in a content less than 0.01 mass percent, may exhibit the effect insufficiently and may fail to allow the aluminum forging to have sufficient levels of creep properties in a high-temperature environment, room-temperature yield strength, and high-temperature yield strength. In contrast, Mg, if present in a content greater than 2.0 mass percent, may cause the aluminum forging to have inferior forgeability because of excessively high strengths. To prevent these, the Mg content may be controlled to 0.01 to 2.0 mass percent, preferably 0.01 to 1.5 mass percent, and more preferably 0.01 to 1.0 mass percent.

Silver (Ag)

[0029] Silver (Ag) forms a fine and homogeneous Ω phase in the aluminum forging and can extremely narrow solute-depleted precipitate free zones (PFZs) where no precipitation phase is present. Ag therefore allows the aluminum forging to have higher levels of room-temperature strengths, high-temperature strengths, and high-temperature creep properties. Ag, if present in a content less than 0.05 mass percent, may insufficiently exhibit the effect. In contrast, Ag, if present in a content greater than 1.0 mass percent, may exhibit the effect in a saturated manner. To prevent these, the Ag content may be controlled to 0.05 to 1.0 mass percent, and preferably 0.05 to 0.7 mass percent.

Manganese (Mn)

[0030] Magnesium (Mn) allows the aluminum forging to include a fibrous structure as the microstructure and to have higher levels of room-temperature strengths and high-temperature strengths. In addition, Mn forms, upon soaking, Al-Mn dispersed particles as precipitates that are compounds thermally stable in the aluminum alloy matrix. The dispersed particles are exemplified by $Al_{20}Cu_2Mn_3$. The dispersed particles have the property of restraining or impeding grain boundary migration after recrystallization and effectively restrain grains from coarsening. Mn, if present in a content less than 0.05 mass percent, may less effectively allow the aluminum forging to have higher levels of room-temperature strengths and high-temperature strengths and may less effectively restrain grains from coarsening. In contrast, Mn, if present in a content greater than 1.5 mass percent, may readily form coarse insoluble intermetallic compounds upon melting/casting and thereby cause defective forming and fracture of the aluminum forging. To prevent these, the Mn content may be controlled to 0.05 to 1.5 mass percent, preferably 0.05 to 1.0 mass percent, and more preferably 0.05 to 0.8 mass percent.

Remainder

[0031] The remainder includes Al and inevitable impurities. The inevitable impurities are exemplified by Ni and Fe. The inevitable impurities (elements) may be contained in a total content of about 0.15 mass percent or less, because the elements, when present in a total content approximately within the range, do not significantly affect the advantageous effects of the present invention.

Zinc (Zn)

[0032] Zinc (Zn) forms fine Mg-Zn compounds and allows the aluminum forging to have higher strengths. Zn, if present in a content less than 0.01 mass percent, may fail to exhibit the effect significantly. In contrast, Zn, if present in a content greater than 0.40 mass percent, may cause the aluminum forging to have lower corrosion resistance. To prevent these, the Zn content may be controlled to preferably 0.01 to 0.40 mass percent, and more preferably 0.10 to 0.30 mass percent.

Silicon (Si)

[0033] Silicon (Si) has the property of allowing the aluminum forging to have higher strengths. Si, when added, may often contribute to increased amounts of precipitates that effectively increase the strengths. Si may effectively restrain dislocation loop in the aluminum alloy. Si therefore effectively contributes to refinement and uniform precipitation of precipitated phases. Si, if present in a content less than 0.01 mass percent, may less exhibit these effects. In contrast, Si, if present in a content greater than 1.0 mass percent, may form coarse intermetallic compounds and thereby cause defective forming, inferior metal fatigue strength, and fracture upon closed-die forging of the aluminum forging in order to form high-speed movable parts such as spinning rotors, rotary impellers, and pistons. To prevent these, the Si content may be controlled to preferably 0.01 to 1.00 mass percent, and more preferably 0.01 to 0.60 mass percent.

Vanadium (V)

[0034] Vanadium (V) precipitates as Al-V compounds in the aluminum alloy matrix and allows the aluminum forging to have a higher fatigue strength in a high-temperature environment. Vanadium also precipitates as Al-V dispersed particles upon soaking, where the Al-V dispersed particles are compounds that are thermally stable in the aluminum alloy matrix. The dispersed particles have the property of impeding grain boundary migration after recrystallization and effectively restrain grains from coarsening. Owing to the effects, vanadium allows the aluminum forging to include a fibrous structure as the microstructure and to have higher levels of room-temperature strengths and high-temperature strengths, in particular fatigue strength in a high-temperature environment. As compared with Zr, Cr, and Mn, vanadium has a relatively low property of allowing a stable phase to precipitate coarsely and is more preferred for higher levels of room-temperature strengths, high-temperature strengths, and fatigue strength in a high-temperature environment as compared with these elements. Based on these, vanadium is preferably selectively contained in a content of 0.01 to 0.15 mass percent. This is preferred for refinement of grains to a size of 500 μm or less so as to more surely allow the aluminum forging to have satisfactory high-temperature properties. Vanadium, if present in a content less than 0.01 mass percent, may less exhibit these effects. In contrast, vanadium, if contained in a content greater than 0.15 mass percent, may readily form coarse insoluble intermetallic compounds upon melting/casting and may thereby cause defective forming and fracture of the aluminum forging. To prevent these, the vanadium content is controlled to preferably 0.01 to 0.15 mass percent, and more preferably 0.01 to 0.10 mass percent.

Chromium (Cr)

[0035] Chromium (Cr) precipitates as Al-Cr dispersed particles upon soaking, where the Al-Cr dispersed particles are compounds thermally stable in the microstructure of the aluminum forging, as with vanadium. The dispersed particles have the property of impeding grain boundary migration after recrystallization and effectively restrain grains from coarsening. Cr, if present in a content less than 0.01 mass percent, may less effectively restrain grains from coarsening. In contrast, Cr, if present in a content greater than 0.30 mass percent, may readily form coarse insoluble intermetallic compounds upon melting/casting and may thereby cause defective forming and fracture of the aluminum forging. To prevent these, the Cr content is controlled to preferably 0.01 to 0.30 mass percent, and more preferably 0.01 to 0.15 mass percent.

Zirconium (Zr) and Scandium (Sc)

[0036] Zirconium (Zr) and scandium (Sc) precipitate respectively as Al-Zr dispersed particles and Al-Sc dispersed parties upon soaking, both of which are compounds thermally stable in the microstructure of the aluminum forging. These dispersed particles have the property of impeding grain boundary migration after recrystallization and effectively restrain grains from coarsening. Zr, if contained in a content less than 0.01 mass percent, and/or Sc, if contained in a content less than 0.01 mass percent, may less effectively restrain grains from coarsening. In contrast, Zr, if present in a content greater than 0.50 mass percent, and/or Sc, if present in a content greater than 1.00 mass percent, may readily form coarse insoluble intermetallic compounds upon melting/casting and may thereby cause defective forming of the aluminum forging. To prevent these, Zr and/or Sc, when to be contained, are preferably contained respectively in contents of 0.01 to 0.50 mass percent and 0.01 to 1.00 mass percent.

Titanium (Ti)

[0037] Titanium (Ti) effectively contributes to grain refinement upon casting. Ti, if present in a content less than 0.01 mass percent, may less exhibit the effect. In contrast, Ti, if present in a content greater than 0.20 mass percent, may form coarse intermetallic compounds. The intermetallic compounds act as fracture origins in the aluminum forging upon forming. Accordingly, Ti, if added in a content greater than 0.20 mass percent, may cause the aluminum forging to have inferior formability. To prevent these, the Ti content may be controlled to 0.01 to 0.20 mass percent.

Iron (Fe)

[0038] Iron (Fe) is generally contaminated as an inevitable impurity. Fe, however, is contaminated typically from scrap, effectively allows the aluminum forging to have higher levels of high-temperature properties, and may be contained in a content up to 0.15 mass percent. Fe, if present in a content greater than 0.15 mass percent, may form insoluble intermetallic compounds and may thereby readily cause defective forming and fracture of the aluminum forging.

Average Grain Size and Grain Aspect Ratio (Length-to-Width Ratio)

[0039] The average grain size and grain aspect ratio of the aluminum forging according to the embodiment of the present invention are approximately determined by the strain state in the material, where the strain state is given by or affected by forging conditions of the hot forging step S3 alone or in combination with the closed-die forging step S4. The strain state appears as the microstructure (the average grain size and grain aspect ratio) as a result of the solution heat treatment step S5, as described above, whereas the average grain size and grain aspect ratio are also affected by the chemical composition. Specifically, the average grain size and grain aspect ratio may be controlled by performing the hot forging step S3 alone or in combination with the closed-die forging step S4 under after-mentioned forging conditions.

[0040] The average grain size can be determined by calculation in the following manner. Initially, a sample of a size of about 15 mm by 15 mm by 10 to 20 mm is cut out from a product or test sample at a portion to be measured, and the sample is embedded in a resin (see FIG. 2). One side (surface) of the resin-embedded sample is polished and electrolytically etched, and photographs of which are taken using an optical microscope. The magnification of the photographs may be optionally adjusted according to the sizes of grains. The grain sizes can be measured typically by a so-called section method. Specifically, the grain sizes may be measured typically in the following manner. As illustrated in FIG. 3, each three lines are drawn vertically and horizontally in each optical photomicrograph (lines a1 to a3 and lines b1 to b3 in FIG. 3), and the number of grain boundaries passing through each line is counted on a line basis. The grain sizes are calculated based on the magnification and size of the photomicrograph and on the number of grain boundaries. The series of measurement procedure is performed on three photomicrographs. From the measurement on nine vertical lines (i.e., three lines by three photomicrographs) and on nine horizontal lines (i.e., three lines by three photomicrographs), each nine vertical and horizontal grain sizes (N = 9) are determined, individually averaged, and defined respectively as vertical and horizontal average grain sizes. The vertical and horizontal average grain sizes are further summed up and averaged, and the resulting average is defined as the average grain size in the present invention.

[0041] The grain aspect ratio (length-to-width ratio) can be determined by defining, of the vertical and horizontal average grain sizes, one being larger than the other as a length (major axis), and the other being smaller as a width (minor axis), and calculating the grain aspect ratio as the ratio of the length to the width.

[0042] After intensive investigations, the present inventors have found that the aluminum forging, when controlled to have an average grain size of 500 μm or less and a grain aspect ratio (length-to-width ratio) of 10 or less, can have higher level of fatigue strength in a high-temperature environment. The aluminum forging, if having an average grain size greater than 500 μm, may readily suffer from not only initial crack that causes fatigue fracture, but also rapid proceeding of crack, and may fail to have higher level of fatigue strength in a high-temperature environment. The aluminum forging, if having a grain aspect ratio (length-to-width ratio) greater than 10, may suffer from large anisotropy in material properties such as fatigue strength in a high-temperature environment, creep properties, and material strengths and may fail to provide a homogeneous product, where the large anisotropy is affected by the orientation of grains. Based on these investigations and considerations, the aluminum forging may be controlled to have an average grain size of 500 μm or less and a grain aspect ratio (length-to-width ratio) of 10 or less. The grain aspect ratio is preferably 7 or less, and more preferably 5 or less.

[0043] The aluminum forging, as having an average grain size of 500 μm or less and a grain aspect ratio (length-to-width ratio) of 10 or less, does not include any of clusters formed by aggregation of fine grains each having a grain size of 1 μm or less; coarse recrystallized grains having a size of several millimeters to several centimeters; and a residual ingot microstructure, where these may be seen in a duplex grain structure. Thus, the aluminum forging has good fatigue strength in a high-temperature environment and can have high-temperature properties (e.g., creep properties) and machinability both at satisfactory levels. The above-mentioned preferred grain microstructure in the aluminum forging does not always refers to a microstructure including 100% of grains having the sizes within the specific ranges alone, but also refers to a microstructure which may further include an as-cast structure and/or a duplex grain structure within such a range as not to adversely affect the properties such as fatigue strength in a high-temperature environment, machinability, creep properties, and other high-temperature properties.

[0044] For example, fine grains having a grain size of 1 μm or less, when being dispersed and present independently, do not adversely affect high-temperature properties such as fatigue strength in a high-temperature environment and creep properties. However, the fine grans, if uniting with each other to form a cluster or an aggregate, may impair the machinability and high-temperature properties. To prevent this, the microstructure after the solution heat treatment preferably has an area percentage of aggregated fine grains of 10% or less, where the fine grains each have a grain size of 1 μm or less.

[0045] Likewise, grains having a grain aspect ratio greater than 10, when dispersed and present independently, do not impair the high-temperature properties such as fatigue strength in a high-temperature environment and creep properties. However, these grams, if uniting with each other to form a cluster or aggregated, may impair the machinability and high-temperature properties. To prevent this, the microstructure after the solution heat treatment preferably has an area percentage of aggregated grains of 10% or less, where the grains each have a grain aspect ratio greater than 10.

Method for Producing Aluminum Alloy Forging

[0046] Next, a method for producing an aluminum forging according to one embodiment of the present invention will be illustrated with reference to FIG. 1. As illustrated in FIG. 1, the method for producing an aluminum forging according to the embodiment includes a casting step S1, a soaking step S2, a hot forging step S3, a solution heat treatment step S5, a quenching step S6, and an artificial aging step S8 and can give the above-mentioned aluminum forging by performing the steps in the specified order.

[0047] The production method may further include, as needed, a closed-die forging step S4 between the hot forging step S3 and the solution heat treatment step S5. The resulting forging undergone the closed-die forging step S4 is also the aluminum forging according to the present invention, as described above.

[0048] Where necessary, the production method may further include a cold compression forming step S7 after the quenching step S6. In addition, after-mentioned T6 temper and/or T61 temper may be performed by the solution heat treatment step S5, the quenching step S6, and the artificial aging step S8. T652 temper may be performed by the solution heat treatment step S5, the quenching step S6, the cold compression forming step S7, and the artificial aging step S8. These temper treatments may be selected as appropriate according to the size and use of a member or part to be produced. The temper (thermal refining) is illustrated herein by taking T6 temper, T61 temper, and T652 temper as examples, but the temper is not limited thereto, and an article undergoing another temper is also included in the present invention.

Casting Step

[0049] The casting step S1 is the step of melting and casting an aluminum alloy having the chemical composition to give an ingot (cast article). The casting technique is not limited and may be selected from common known techniques. Typically, an ingot can be prepared by melting and adjusting an aluminum alloy so as to have a chemical composition within the range specified in the present invention, and casting the molten aluminum alloy by a casting technique selected as appropriate from common melting/casting techniques such as continuous casting-directed rolling and semi-continuous casting (direct-chill casting).

Soaking Step

[0050] The soaking step S2 is preferably performed at a holding temperature of 500°C to 545°C, where the temperature falls within such a temperature range as not to cause eutectic melting and is as high as possible. The soaking time can be appropriately set as such a time as to allow intermetallic compounds to effectively disperse and diffuse in the base metal, according to the chemical composition, ingot size, and time suitable for production. The soaking is preferably performed for a time of typically from 8 to 100 hours. The soaking, when performed under these conditions, may allow intermetallic compounds to be effectively dissolved in and diffuse in the base metal. This allows the intermetallic compounds to have smaller sizes. For some types of intermetallic compounds, a multistage soaking process is more effective so as to allow the intermetallic compounds to have smaller sizes without eutectic melting, where soaking is performed in at least two stages in the multistage soaking process.

[0051] The multistage soaking process may be performed by setting appropriate conditions according to the type of the intermetallic compound(s), where the conditions are exemplified by the rate of temperature rise, soaking temperature, and process time. Typically, in an exemplary multistage soaking process, a heat treatment is performed at a relatively low temperature within the soaking temperature range (500°C to 545°C) so as to allow intermetallic compound(s) to be dissolved and to diffuse. This heat treatment is suitable for individual intermetallic compounds. Next, another heat treatment is performed at a relatively high temperature within the soaking temperature range to allow the intermetallic compound(s) to have smaller sizes. Such soaking process in which the temperature is adjusted in multiple stages is effective.

[0052] There is another process to obtain similar effects to the multistage soaking process. In the process, the temperature is raised up to the soaking temperature at a relatively low rate, where the temperature rise is performed within such a temperature range as not to cause eutectic melting of intermetallic compounds. This process can be performed in combination with the multistage soaking process. In this case, the rate of temperature rise should be set as appropriate according typically to the types, sizes, and amounts of the intermetallic compounds.

[0053] These soaking processes, when employed, can allow intermetallic compounds to have smaller sizes while preventing them from eutectic melting. The size reduction of the intermetallic compounds may restrain the fatigue fracture originated from the intermetallic compounds and may allow the aluminum forging to have higher fatigue strength in a high-temperature environment. The soaking allows individual elements to uniformly diffuse from the intermetallic compounds into the base metal, thus induces solute strengthening and precipitation strengthening, and thereby allows the base metal to have higher strengths. Concurrently, the soaking also allows the aluminum alloy to have still higher levels of elongation, impact resistance value, and fatigue strength in a high-temperature environment.

[0054] In addition, the soaking invites homogenization of microsegregation formed by solidification, precipitation of supersaturated solute elements, and change of a metastable phase into an equilibrium phase. The soaking, if performed at a temperature lower than 500°C, may not cause solid-solutionization (dissolution) of intermetallic compounds such as precipitates in the ingot and may offer sufficient homogenization. In contrast, soaking, if performed at a temperature higher than 545°C, may more possibly cause burning. To prevent these, the soaking may be performed at a temperature of from 500°C to 545°C. In the multistage soaking, the heat treatment conditions should be set according to the type(s) of the intermetallic compound(s), as described above. Likewise, in the soaking in which the temperature is raised at a relatively low rate, the heat treatment conditions should be set according to the type(s) of the intermetallic compound(s).

Hot Forging Step

[0055] The hot forging step S3 is the step of subjecting the soaked ingot to hot forging at a forging temperature of 180°C to 360°C at a forging ratio of 1.5 or more. Strain is introduced into the material inside under controlled forging conditions in the hot forging step S3 and in the after-mentioned closed-die forging step S4. The forging conditions are exemplified by forging temperature, forging rate, and forging direction on the material. How the strain accumulates (e.g., direction and density) approximately determines the grain size and the grain aspect ratio of grains as appeared in the subsequent solution heat treatment step S5. The grains in these forging steps correspond to grains in the ingot, only except for being deformed. The grain size appeared in this stage little affects the final grain size, but when the ingot has a small grain size, a workpiece after the solution heat treatment step tends to have a small grain size. The strain in the material (workpiece) introduced by the forging steps is released to newly form grains when the material is placed in a high-temperature environment in the solution heat treatment step S5.

[0056] The hot forging temperature conditions, together with the after-mentioned forging ratio, are important so as to allow the aluminum alloy to have higher levels of properties, in particular, a higher level of fatigue strength in a high-temperature environment. Specifically, the hot forging temperature conditions are important to control the grain size and grain shape in the aluminum alloy after the solution heat treatment step S5. The hot forging, as performed at a forging temperature of 180°C to 360°C, enables the control of grain size and grain shape and enables stable production of the aluminum forging. The hot forging, if performed at a forging temperature lower than 180°C, may often cause crack in the aluminum alloy upon hot forging, and this may impede the forging process itself In contrast, the hot forging, if performed at a forging temperature higher than 360°C, may cause the aluminum alloy microstructure to often include coarse grains. This may cause the resulting aluminum forging to have inferior high-temperature properties and to fail to be an aluminum forging having excellent high-temperature properties. To prevent these, the hot forging may be performed at a forging temperature of 180°C to 360°C, and preferably 180°C to lower than 280°C. The forging, if performed disproportionately in one direction, may cause strain to accumulate disproportionately in one direction. This may particularly cause grains after the solution heat treatment step S5 to be elongated lengthwise to thereby have a grain aspect ratio greater than 10, may thereby cause the aluminum forging to have inferior high-temperature properties, and may impede the production of an aluminum forging having excellent high-temperature properties. To control the grain aspect ratio to 10 or less, such a forging process as to restrain the disproportion of the strain accumulation is effective. Specifically, forging in two or more directions (namely, two- or higher-order-directional forging) is effective.

[0057] The microstructure of the aluminum alloy after the solution heat treatment is significantly affected by the forging ratio of the hot forging. The forging ratio may be controlled to 1.5 or more so as to control the microstructure of the aluminum forging after the solution heat treatment to have a grain size and grain shape as specified in the present invention. The forging, if performed at a forging ratio less than 1.5, may readily cause the aluminum alloy microstructure to include duplex grains (mixed grains). The forging is preferably performed not in only one direction, but in at least two different directions, and more preferably in three or more different directions, at a forging ratio in each direction of 1.5 or more. The forging performed in two different directions is also referred to as "two-directional forging"; and the forging performed in three different directions is also referred to as "three-directional forging". Hereinafter the two-directional forging and three-directional forging will be illustrated.

[0058] The ingot to be subjected to two-directional forging or three-directional forging may be in the form of a rectangular parallelepiped, cube, or cylinder. The ingot in the form of a rectangular parallelepiped or cube may be formed by preforging and/or cutting before the hot forging. For example, assume that the ingot is in the form of a rectangular parallelepiped. This ingot has a side A, a side B, and a side C, where the side B is perpendicular to the side A, and the side C is perpendicular both to the side A and the side B. Specifically, the ingot includes six sides, i.e., assuming that the side A defines a top face, the side A, a side (underside) facing the side A, the lateral side B, a side facing the lateral side B, the side C, and a side facing the side C. Typically, the side B and the side C are forged so as to cause the side A to have an area half the initial area (the forging ratio of the side A is 2S). Next, the side A and the side C are forged so as to cause the side B to have an area half the initial area (the forging ratio of the side B is 2S). The forging procedure until this is referred to as "two-directional forging". Next, the side A and the side B are forged so as to cause the side C to have an area half the initial area (the forging ratio of the side C is 2S). The forging procedure until this is referred to as "three-directional forging".

[0059] The forging step in the present invention may further include one or more passes of two-directional forging or three-directional forging, in addition to one pass of two-directional forging or three-directional forging. The upper limit of the forging is not critical and may be determined according to the desired size of the forging. Obviously, the forging may further include, after one or more passes of two-directional forging or three-directional forging, one or two passes of forging in any direction (on any side). Namely, the forming may be any of, for example, four-directional forging, five-directional forging, six-directional forging, seven-directional forging, and eight-directional forging. Such forging of the ingot by at least two-directional forging can increase the material strengths, can remove grain orientation (can uniformize the material), and thereby allows the aluminum forging to have a higher fatigue strength in a high-temperature environment.

Closed Die Forging Step

[0060] The closed-die forging step S4 is an optional step that may be performed between the hot forging step S3 and the solution heat treatment step S5 and is the step of subjecting the forging to closed-die forging at a temperature of 180°C to 360°C. The method, when performed to produce a product having some shape, may employ the closed-die forging step S4 after the hot forging step S3. The forging temperature conditions in the closed-die forging step S4 are also important so as to offer higher levels of the properties of the aluminum alloy, in particular, a higher level of the fatigue strength in a high-temperature environment. Specifically, the conditions are important so as to control the size and shape of grains in the aluminum alloy after the solution heat treatment step S5. As with the hot forging step S3, forging in the closed-die forging step, if performed disproportionately in one direction, may cause strain to accumulate disproportionately in one direction and may particularly cause grains after the solution heat treatment step S5 to be elongated lengthwise to thereby have a grain aspect ratio greater than 10. This may cause the aluminum forging to have inferior high-temperature properties and may impede the production of an aluminum forging having excellent high-temperature properties with good reproducibility. To control the grain aspect ratio to 10 or less, such a closed-die forging process as to restrain disproportional strain accumulation is effectively planned and employed in the closed-die forging step S4. For example, shapes of the dies (tools) may be adjusted so that the forging direction upon closed-die forging is not tilted toward one direction.

[0061] The closed-die forging is preferably performed at a temperature of 180°C to 360°C, as with the hot forging. This can control the size and shape of grains and enables stable production of the aluminum forging. The closed-die forging, if performed at a temperature lower than 180°C, may often cause cracks during the process, and this may impede the forging process itself In contrast, the closed-die forging, if performed at a forging temperature higher than 360°C, may readily cause the aluminum forging to include coarse grains in the microstructure. This may cause the aluminum forging to have inferior high-temperature properties and may impede production of an aluminum forging having excellent high-temperature properties with good reproducibility. To prevent these, the closed-die forging may be performed at a temperature of preferably 180°C to 360°C, and more preferably 180°C to lower than 280°C.

Solution Heat Treatment Step and Quenching Step

[0062] Next, the solution heat treatment step S5 and the quenching step S6 will be illustrated. The solution heat treatment step S5 is the step of subjecting the forging after hot forging to a solution heat treatment at a holding temperature of 510°C to 545°C. The quenching step S6 is the step of subjecting the forging after the solution heat treatment to quenching at an average cooling rate in a temperature range of 400°C to 290°C of 10°C/min. to less than 30000°C/min.

[0063] The solution heat treatment step S5 and the quenching step S6 are preferably performed under conditions prescribed in Japanese Industrial Standard (JIS) H 4140 or Aerospace Material Specifications (AMS)-H-6088 so as to allow soluble intermetallic compounds to be re-dissolved and to be resistant to reprecipitation as much as possible. However, the solution heat treatment, if performed at an excessively high temperature, may cause burning and may cause the aluminum forging to have significantly inferior mechanical properties even when the heat treatment is performed according typically to the standard specified in AMS-H-6088. On the contrary, the solution heat treatment, if performed at a temperature lower than the lower-limit temperature, may cause the aluminum forging to have a yield strength after artificial aging at an sufficient level for the objects of the present invention, and such high-temperature solution heat treatment itself is difficult to perform. To prevent these, the solution heat treatment may be performed at a temperature in the range of from 510°C (lower limit) to 545°C (upper limit).

[0064] A furnace usable in temper treatments (thermal refining; heat treatments) such as solution heat treatment and quenching may be selected as appropriate typically from batch furnaces, continuous annealing furnaces, salt-bath furnaces, and oil furnaces. A cooling process for use in the quenching may also be selected as appropriate typically from water immersion, hot water immersion, boiling water immersion, polymer solution immersion, water injection, and air injection. The polymer for use in the polymer immersion is exemplified by polyoxyethylene-propylene-polyethers. Specifically, the polymer usable herein is exemplified by UCON™ Quenchant (trade name) supplied by The Dow Chemical Company (Midland, MI, U.S.A.).

[0065] The quenching step S6 is important so as to allow the θ' phase and/or the Ω phase to finely and densely precipitate in the (100) plane and/or the (111) plane of the aluminum alloy upon the subsequent artificial aging performed at a high temperature and to allow the aluminum forging after the artificial aging to have higher strengths. The quenching, if performed at an excessively low average cooling rate in the temperature range of 400°C to 290°C in the cooling process, may cause coarse θ' phase and coarse Ω phase to precipitate in the middle of cooling and may cause the aluminum forging after artificial aging to have inferior material strengths. Products (aluminum forgings) to be produced have wide-ranging sizes ranging from several tens of millimeters to several meters, and articles to be quenched thereby have wide-ranging wall thicknesses. The cooling rate in quenching should therefore be adjusted as appropriate according to the use conditions and use environment of a target product. After intensive investigations on various products, the present inventors have found that the cooling process in the temperature range of 400°C to 290°C, if performed at an average cooling rate less than 10°C/min., may cause the aluminum forging to have inferior material strengths and to fail to have a satisfactory fatigue strength in a high-temperature environment. The higher the cooling rate, the better for effectively high strengths. However, the quenching, if performed at an average cooling rate in the specific temperature range of 30000°C/min. or more, may be difficult to control in its quenching rate. To prevent this, quenching is preferably performed at an average cooling rate in the temperature range of 400°C to 290°C of 10°C/min. to less than 30000°C/min.. The lower limit of the average cooling rate in the temperature range of 400°C to 290°C is typically preferably 15°C/min., and more preferably 20°C/min. The upper limit of the average cooling rate in the temperature range of 400°C to 290°C is not critical, as long as being less than 30000°C/min., but is typically more preferably 20000°C/min., furthermore preferably 10000°C/min., and still more preferably 6000°C/min.

Cold Compression Forming Step

[0066] The cold compression forming step S7 is an optional step that may be performed after the quenching step S6. The cold compression forming step S7, when performed, enables the correction or straightening of strain generated upon quenching and allows the final product to have higher levels of high-temperature properties such as yield strength and creep rupture strength. The cold compression forming may be performed typically with a cold rolling mill or with a stretcher in combination with cold forging. The cold compression forming, if performed to an excessively small amount of compression, may fail to sufficiently effectively reduce the residual stress. In contrast, the cold compression forming, if performed to an excessively large amount of compression, may cause the θ' phase to precipitate in a larger amount during the artificial aging or upon the use of the aluminum forging in a high-temperature environment, and may thereby readily cause the aluminum forging to have a lower yield strength. To prevent these, the cold compression forming is preferably performed to a working ratio of 1% to 5%.

T6 Temper

[0067] Assume that the aluminum forging is formed as a small-sized part or piston having a diameter of about 100 mm or less. The resulting part or piston can be subjected to working such as cutting without problems even when it has relatively large residual stress. In this case, the aluminum forging after the solution heat treatment and quenching is subjected to the artificial aging to give a temper T6 material In this process, the quenching temperature is preferably set to 50°C or lower so as to obtain higher levels of strength properties and high-temperature properties even when the article has relatively large residual stress.

T61 Temper

[0068] Assume that the aluminum forging is formed as a large-sized product such as a rotary impeller. The large-sized product (aluminum forging) undergoes quenching at significantly different cooling rates in a product surface and in a central portion and thereby has a high residual stress greater than about 98 MPa (10 kgf/mm^2) in the surface. The aluminum forging, if having such a high residual stress in the surface, may have large strain upon cutting, and this may significantly impede precise cutting. In addition, the residual stress may cause the aluminum forging to suffer from fracture due typically to cracks generated during cutting. Even when fracture due typically to cracks is not generated in the aluminum forging during cutting, cracks may be generated from intermetallic compounds (such as precipitates) remaining in the material, or generated from slight surface defects generated during product transportation. The generated cracks may readily spread and grow during long-time use of the product and may possibly lead to fracture ultimately. To prevent this, the product (aluminum forging) such as a rotary impeller whose residual stress may become an issue is preferably formed as a temper T61 material by performing, after the solution heat treatment, water quenching at a relatively high temperature of 70°C or higher, and subjecting the resulting workpieoe to artificial aging. This is preferred so as to remove or relieve the residual stress to a level of preferably about 29 MPa (3.0 kgf/mm^2) or less.

T652 Temper

[0069] The product (aluminum forging) in some uses should be strictly controlled on residual stress regardless of the size of the product. The product of this type is preferably formed as a temper T652 material by performing cold compression forming so as to remove or relive the residual stress to a level of preferably about 29 MPa (3.0 kgf/mm^2) or less and subjecting the resulting workpiece to artificial aging. This is preferred to minimize the residual stress. To form the temper T652 material, for example, the quenching temperature is preferably set to 50°C or lower. The cold compression forming, if performed at an excessively small magnitude, may fail to effectively contribute to sufficient reduction of residual stress even when the quenching temperature is set to 50°C or lower. In contrast, the cold compression forming, if performed at an excessively large magnitude, may cause the θ' phase to precipitate in a larger amount during the artificial aging or during use at a high temperature even when the quenching temperature is set to 50°C or lower. Thus, the resulting aluminum forging may readily have a low yield strength. To prevent these, the cold compression forming is preferably performed to a working ratio of 1% to 5%.

Artificial Aging Step

[0070] The artificial aging step S8 is performed after the quenching step S6. When the cold compression forming step S7 is performed after the quenching step S6, the artificial aging step S8 is performed after the cold compression forming step S7. The artificial aging step S8 is the step of artificially aging (temper aging) the forging after quenching (or after cold compression forming).

[0071] The artificial aging in the temper treatments is performed to impart, to the aluminum forging, room-temperature yield strength, high-temperature properties such as high-temperature yield strength and creep rupture strength, and fatigue strength in a high-temperature environment. The artificial aging may allow the Ω phase and the θ' phase to precipitate respectively in the (111) plane and the (100) plane of the aluminum alloy and may allow the aluminum forging to have the above-mentioned properties. The artificial aging may be performed by any procedure not limited, as long as allowing the Ω phase and θ' phase to precipitate in such states that a satisfactory fatigue strength in a high-temperature environment is obtained in the aluminum forging according to the embodiment of the present invention. The procedure is preferably such that the aluminum forging can have the desired levels of room-temperature yield strength, high-temperature properties such as high-temperature yield strength and creep rupture strength, and metal fatigue properties.

[0072] The aluminum forging and the production method thereof each according to one embodiment of the present invention have been illustrated. The aluminum forging according to the embodiment of the present invention, as having an average grain size of 500 μm or less and a grain aspect ratio (length-to-width ratio) of 10 or less, can have excellent fatigue strength in a high-temperature environment.

[0073] The method for producing an aluminum forging according to the embodiment of the present invention can produce an aluminum forging having an average grain size of 500 μm or less and a grain aspect ratio (length-to-width ratio) of 10 or less. The method can thereby produce an aluminum forging having excellent fatigue strength in a high-temperature environment.

Examples

[0074] Next, the present invention will be illustrated in further detail with reference to several examples below. It should be noted, however, that the examples are never construed to limit the scope of the present invention.

Test Samples 1 to 23

[0075] Ingots corresponding to Test Samples 1 to 23 in Table 2 were formed by ingot-making using aluminum alloys having chemical compositions given as Compositions 1 to 17 in Table 1. The ingots each had a diameter of 500 mm and a length of 2000 mm. The ingots were soaked at 510°C for 15 hours in an air furnace. The soaked ingots were hot-forged by three-directional forging at a forging ratio in each direction of 1.5 or more so as to adjust the average grain size and grain aspect ratio. The forging temperatures in the hot forging were set within the range of 180°C to 360°C. Next, the forgings after three-directional forging were cut by machining to give materials of 50-mm square (thick) by 300 mm long. The cut materials were placed in the air furnace, heated at a heating rate of 200°C/hour, and subjected to a solution heat treatment at 530°C for 3 hours, quenched in hot water of 70°C to 91°C at an average cooling rate of about 30°C/min. to 120°C/min., artificially aged at 190°C for 18 hours, and yielded Test Samples 1 to 23 each as a temper T61 material Test Sample 14 was prepared through hot forging at a forging temperature of 400°C; and Test Sample 15 was prepared through one-directional forging performed in one direction.

[0076] In the chemical compositions given in Table 1, the remainder is Al and inevitable impurities. The underlined data in Table 1 indicate that the data do not meet the condition(s) specified in the present invention.

[Table 1]

	Chemical composition (mass percent)										
	Cu	Mg	Ag	Mn	Zn	Si	V	Cr	Zr	Sc	Ti
Composition 1	6.3	0.3	0.50	0.3	0.02	0.05	0.09	<0.01	0.04	<0.01	0.04
Composition 2	6.3	0.3	0.10	0.3	0.02	0.05	0.08	<0.01	0.03	<0.01	0.04
Composition 3	5.5	0.3	0.50	0.3	0.03	0.05	<0.01	<0.01	0.03	<0.01	0.04
Composition 4	4.0	0.3	0.45	0.3	0.02	0.25	0.07	<0.01	0.03	<0.01	0.05
Composition 5	5.0	0.3	0.50	0.8	0.02	0.05	<0.01	<0.01	0.03	<0.01	0.03
Composition 6	6.5	0.4	0.55	0.3	0.02	0.05	<0.01	<0.02	0.03	<0.01	0.04
Composition 7	6.5	0.3	0.60	0.3	0.25	0.05	0.08	<0.03	0.03	<0.02	0.04
Composition 8	5.0	0.3	0.50	0.3	0.02	0.35	0.08	<0.01	0.03	<0.01	0.04
Composition 9	6.0	0.3	0.55	0.3	0.02	0.05	<0.01	0.1	0.10	0.1	0.06
Composition 10	<u>2.9</u>	0.3	0.55	0.3	0.02	0.05	<0.01	<0.01	0.03	<0.01	0.03
Composition 11	5.0	<u><0.01</u>	0.50	0.3	0.02	0.05	<0.01	<0.01	0.03	<0.01	0.04
Composition 12	6.0	0.3	0.55	<u>0.03</u>	0.02	0.05	0.08	<0.01	0.03	<0.01	0.04
Composition 13	5.0	0.3	<u>0.04</u>	0.3	0.02	0.05	<0.01	<0.01	0.03	<0.01	0.04
Composition 14	7.0	0.3	0.55	0.3	0.02	0.05	<0.01	<0.01	0.03	<0.01	0.03
Composition 15	5.0	2.0	0.50	0.3	0.02	0.05	<0.01	<0.01	0.03	<0.01	0.04
Composition 16	6.0	0.3	0.55	1.5	0.02	0.05	0.08	<0.01	0.03	<0.01	0.04
Composition 17	5.0	0.3	1.00	0.3	0.02	0.05	<0.01	<0.01	0.03	<0.01	0.04

[0077] The prepared test samples were each examined to measure average grain size and grain aspect ratio and to determine the fatigue strength in a high-temperature environment in the following manner.

Average Grain Size and Grain Aspect Ratio Measurement

[0078] A sample of a size of about 15 mm by 15 mm by 10 to 20 mm was cut out from each test sample and embedded in a resin (see FIG. 2). One side (surface) of the resin-embedded sample was polished, electrolytically etched, and photographs of which were taken using an optical microscope. The magnification of the photographs was optionally adjusted according to the sizes of grains.

[0079] The grain sizes were measured by the so-called section method. Specifically, the grain sizes were measured in the following manner. As illustrated in FIG. 3, each three lines were drawn vertically and horizontally in each optical photomicrograph (lines a1 to a3 and lines b1 to b3 in FIG. 3), and the numbers of grain boundaries passing through the lines were counted on a line basis. The grain sizes were calculated based on the magnification and size of the photomicrograph and on the number of grain boundaries. The series of measurement procedure was performed on three photomicrographs. From the measurement on nine vertical lines (i.e., three lines by three photomicrographs) and on nine horizontal lines (i.e., three lines by three photomicrographs), each nine vertical and horizontal grain sizes (N = 9) were determined, individually averaged, and defined respectively as vertical and horizontal average grain sizes. The vertical and horizontal average grain sizes were further summed up and averaged, and the resulting average was defined as the average grain size.

[0080] The grain aspect ratio (length-to-width ratio) was determined by defining, of the vertical and horizontal average grain sizes, one being larger than the other as a length, and the other being smaller as a width, and calculating the grain aspect ratio as the ratio of the length to the width.

Fatigue Strength in High-Temperature Environment

[0081] Each of the prepared T61 temper materials was formed into a test specimen as follows. The test specimen was subjected to a metal fatigue test in a high-temperature environment at 150°C at a maximum stress of 130 MPa and a stress ratio of -1. The test specimen was a round-bar test specimen having a parallel portion diameter of 6 mm and a parallel portion length of 13.55 mm and being finished with a #1000 emery paper. The test specimen was subjected to a rotary bending fatigue test as the metal fatigue test to measure a number of cycles before rupture. The measured number of cycles before rupture is given in Table 2. The "number of cycles before rupture" refers to the number of repeated cycles until rupture occurred in the rotary bending fatigue test. Underlined data in Table 2 are data that do not meet the condition(s) specified in the present invention. A sample having a number of cycles before rupture of less than 5.0e6 (less than 5.0×10^6) was evaluated as "poor"; a sample having a number of cycles before rupture of 5.0e6 to less than 8.0e6 (5.0×10^6 to less than 8.0×10^6) was evaluated as "weak"; and a sample having a number of cycles before rupture of 8.0e6 or more (8.0×10^6 or more) was evaluated as "good". Samples evaluated as "good" were accepted herein, whereas samples evaluated as "weak" or "poor" were rejected.

[Table 2]

Test sample	Chemical composition	Average grain size (μm)	Grain aspect ratio (length-to-width ratio)	Number of cycles before rupture
1	Composition 1	150	3	Good
2	Composition 2	200	3	Good
3	Composition 3	300	4	Good
4	Composition 4	500	3	Good
5	Composition 5	100	2	Good
6	Composition 6	250	3	Good
7	Composition 7	180	2	Good
8	Composition 8	80	2	Good
9	Composition 9	400	4	Good
10	Composition 1	50	1.5	Good
11	Composition 1	70	2	Good
12	Composition 1	300	6	Good
13	Composition 1	500	9	Good
14	Composition 1	<u>800</u>	3	Weak
15	Composition 1	500	<u>11</u>	Weak
16	Composition 10	200	2.5	Poor
17	Composition 11	300	3	Poor
18	Composition 12	150	3	Weak
19	Composition 13	200	2	Poor
20	Composition 14	200	2	Good
21	Composition 15	200	3	Good
22	Composition 16	300	2	Good
23	Composition 17	150	3	Good

[0082] As demonstrated in Table 2, Test Samples 1 to 13 and 20 to 23 met conditions specified in the present invention and had good fatigue strength in a high-temperature environment (examples according to the present invention). In contrast, Test Samples 14 to 19 did not meet the conditions specified in the present invention and failed to have good fatigue strength in a high-temperature environment (comparative examples).

[0083] Specifically, Test Sample 14 underwent forging at a temperature of 400°C and had an average grain size not meeting the condition specified in the present invention. Test Sample 14 resulted in having not good fatigue strength in a high-temperature environment. Test Sample 15 was prepared through forging in one direction and had a grain aspect ratio (length-to-width ratio) not meeting the condition specified in the present invention. Test Sample 15 resulted in having not good fatigue strength in a high-temperature environment.

[0084] Test Sample 16 had a Cu content lower than the lower limit, failed to have sufficient material strengths, and resulted in having not good fatigue strength in a high-temperature environment. Test Sample 17 had a Mg content of lower than the lower limit, failed to have sufficient material strengths, and resulted in having not good fatigue strength in a high-temperature environment. Test Sample 18 had a Mn content of lower than the lower limit, thereby had a large grain size, and failed to have sufficient fatigue strength. Test Sample 18 thereby resulted in having not good fatigue strength in a high-temperature environment. Test Sample 19 had a Ag content of lower than the lower limit and failed to sufficiently narrow PFZs. Test Sample 19 thereby resulted in having not good fatigue strength in a high-temperature environment.

Test Sample 24

[0085] Next, Test Sample 24 was prepared using the aluminum alloy having Composition 1 as given in Table 1. Test Sample 24 was prepared by the procedure of Test Sample 1, except for performing three-directional forging at a forging ratio in each direction of 2. The prepared Test Sample 24 was subjected to a rotary bending fatigue test under the conditions as above to evaluate the fatigue strength in a high-temperature environment. As a result, Test Sample 24 was found to have satisfactorily good fatigue properties in a high-temperature environment at 150°C (example according to the present invention) as with Test Samples 1 to 13, 20 to 23.

Test Samples 25 to 35

[0086] Next, with reference to Table 3, Test Samples 25 to 35 were prepared using the aluminum alloy having Composition 1 by the procedure of Test Sample 1, except for varying or controlling the hot forging temperature (°C) and the average cooling rate (°C/min.) in the temperature range of 400°C to 290°C after the solution heat treatment, as given in Table 3. Test Samples 25 to 35 were subjected to rotary bending fatigue tests under conditions as above to measure the fatigue strength in a high-temperature environment. The evaluation results of the fatigue strength in a high-temperature environment in Test Samples 25 to 35, together with the hot forging temperature (°C) and the average cooling rate (°C/min.), are given in Table 3. In Table 3, underlined data indicate that the data do not meet the condition specified in the present invention.

[Table 3]

Test sample	Chemical composition	Hot forging temperature (°C)	Average cooling rate (°C/min.)	Number of cycles before rupture
25	Composition 1	200	15	Good
26	Composition 1	200	6000	Good
27	Composition 1	270	15	Good
28	Composition 1	270	30	Good
29	Composition 1	270	200	Good
30	Composition 1	270	6000	Good
31	Composition 1	300	30	Good
32	Composition 1	300	200	Good
33	Composition 1	<u>400</u>	15	Poor
34	Composition 1	<u>400</u>	6000	Poor
35	Composition 1	270	<u>5</u>	Poor

[0087] Test Samples 25 to 32 met the conditions specified in the present invention, i.e., each had an average grain size of 500 μm or less and a grain aspect ratio (length-to-width ratio) of 10 or less, and thereby had good fatigue strength in a high-temperature environment (examples) as demonstrated in Table 3. In particular, Test Samples 26 and 30 underwent cooling after the solution heat treatment at a high average cooling rate in the temperature range of 400°C to

290°C and had a high tensile strength (not indicated in Table 3). In contrast, Test Samples 33 to 35 did not meet the condition(s) specified in the present invention and thereby resulted in having not good fatigue strength in a high-temperature environment (comparative examples).

[0088] Specifically, Test Samples 33 and 34 underwent hot forging performed at a temperature higher than the upper limit, thereby had a large grain size (average grain size greater than 500 μm), and failed to have sufficient fatigue strength. Test Samples 33 and 34 thereby resulted in having not good fatigue strength in a high-temperature environment. Test Sample 35 underwent cooling in the specific temperature range at an average cooling rate lower than the lower limit, thereby failed to have sufficient material strengths (yield strength less than 350 MPa), and failed to have sufficient fatigue strength. Test Sample 35 thereby resulted in having not good fatigue strength in a high-temperature environment.

Test Sample 36

[0089] Next, Test Sample 36 was prepared using the aluminum alloy having Composition 1 in Table 1 through three-directional forging as the hot forging at a forging ratio in each direction of 2. Test Sample 36 was prepared by the procedure of Test Sample 1, except for performing, after the hot forging, closed-die forging at 270°C to give an approximately disc-like workpiece. The prepared Test Sample 36 was subjected to a rotary bending fatigue test under conditions as above to evaluate the fatigue strength in a high-temperature environment. Test Sample 36 was found to have satisfactory fatigue properties in a high-temperature environment at 150°C (example) as with Test Samples 1 to 13 and 20 to 23.

Claims

1. An aluminum alloy forging formed by forging an aluminum alloy, the aluminum alloy Comprising:

Cu in a content of 3.0 to 8.0 mass percent;
Mg in a content of 0.01 to 2.0 mass percent;
Ag in a content of 0.05 to 1.0 mass percent;
Mn in a content of 0.05 to 1.5 mass percent,
with the remainder consisting of Al and inevitable impurities,
the aluminum alloy forging having an average grain size of 500 μm or less,
the aluminum alloy forging having a grain aspect ratio (length-to-width ratio) of 10 or less.

2. The aluminum alloy forging according to claim 1,
wherein the aluminum alloy further comprises at least one element selected from the group consisting of

Zn in a content of 0.01 to 0.40 mass percent;
Si in a content of 0.01 to 1.00 mass percent;
V in a content of 0.01 to 0.15 mass percent;
Cr in a content of 0.01 to 0.30 mass percent;
Zr in a content of 0.01 to 0.50 mass percent;
Sc in a content of 0.01 to 1.00 mass percent; and
Ti in a content of 0.01 to 0.20 mass percent.

3. A method for producing an aluminum alloy forging, the method comprising, in a specified order as follows, the steps of

melting and casting an aluminum alloy comprising the chemical composition as specified in one of claims 1 and 2 to give an ingot;
soaking the ingot at a holding temperature of 500°C to 545°C;
hot-forging the soaked ingot at a forging temperature of 180°C to 360°C and at a forging ratio of 1.5 or more to give a forging;
subjecting the forging to a solution heat treatment at a holding temperature of 510°C to 545°C;
quenching the solution-heat-treated forging at an average cooling rate in a temperature range of 400°C to 290°C of 10°C/min. to less than 30000°C/min.; and
artificially aging the quenched forging.

4. The method for producing an aluminum alloy forging according to claim 3, wherein the step of hot forging comprises performing forging of the ingot sequentially in at least two different directions.

5. The method for producing an aluminum alloy forging according to claim 3, wherein the step of hot forging comprises performing forging of the ingot in three different directions.

6. The method for producing an aluminum alloy forging according to any one of claims 3 to 5,
wherein the forging is performed at a temperature of 180°C to lower than 280°C.

7. The method for producing an aluminum alloy forging according to any one of claims 3 to 5,
further comprising the step of closed-die forging between the step of hot forging and the step of solution heat treatment, the step of closed-die forging comprising forging the forging in closed dies at a temperature of 180°C to 360°C.

8. The method for producing an aluminum alloy forging according to claim 7, wherein the closed-die forging is performed at a temperature of from 180°C to lower than 280°C.

FIG. 1

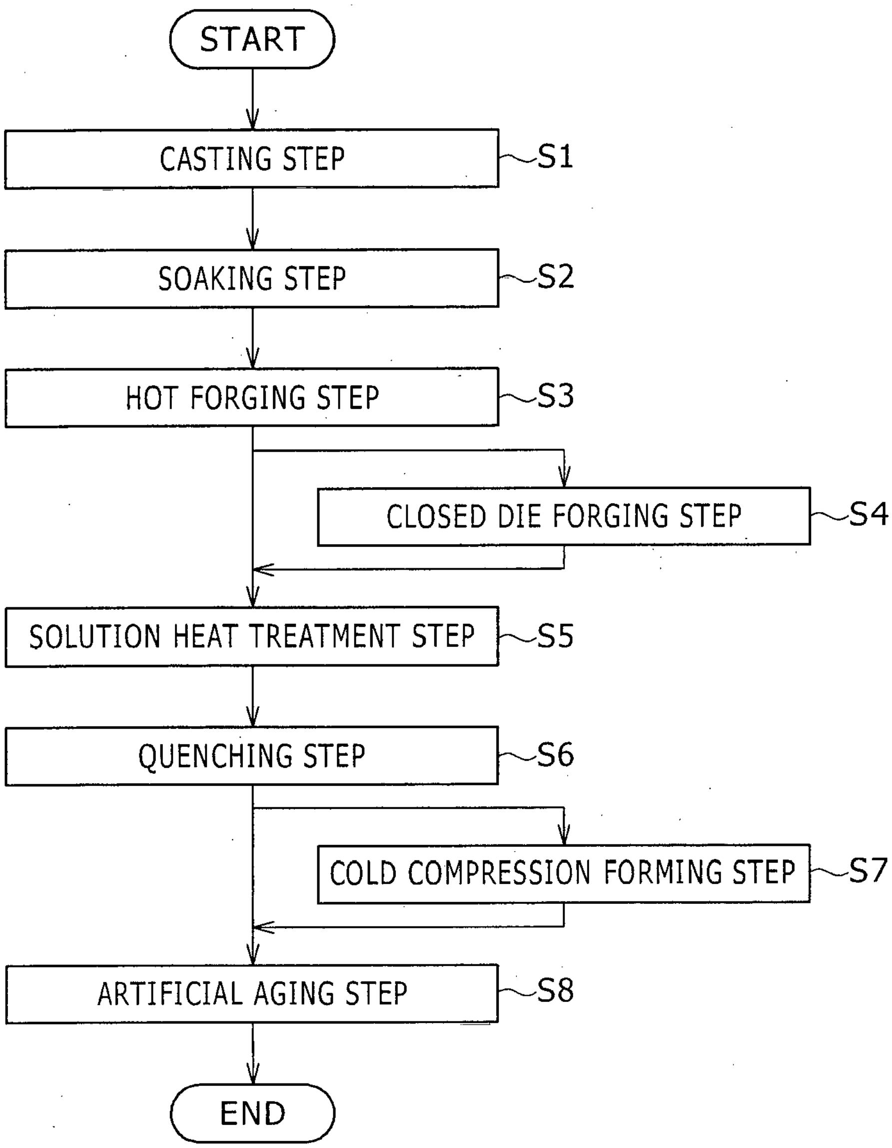

START
CASTING STEP
S1
SOAKING STEP
S2
HOT FORGING STEP
S3
CLOSED DIE FORGING STEP
S4
SOLUTION HEAT TREATMENT STEP
S5
QUENCHING STEP
S6
COLD COMPRESSION FORMING STEP
S7
ARTIFICIAL AGING STEP
S8
END

FIG. 2

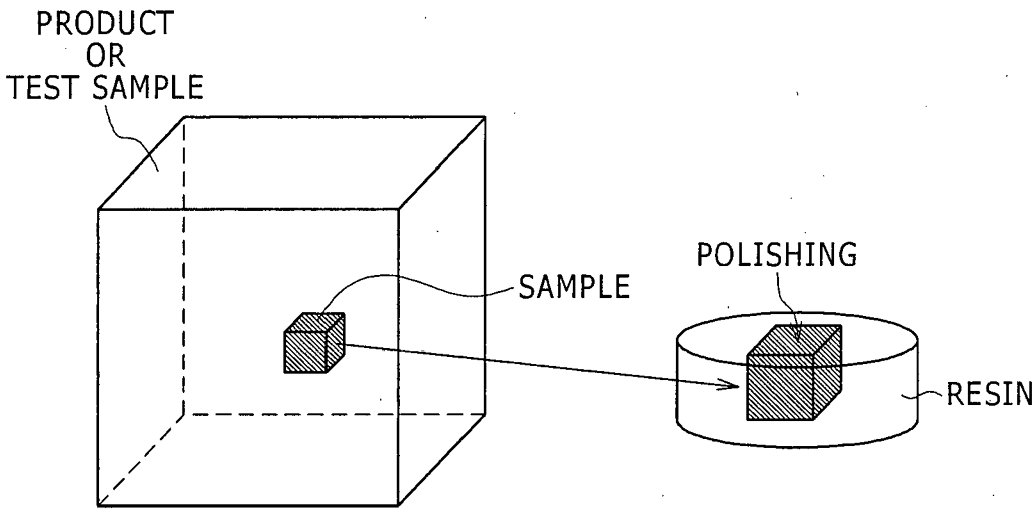
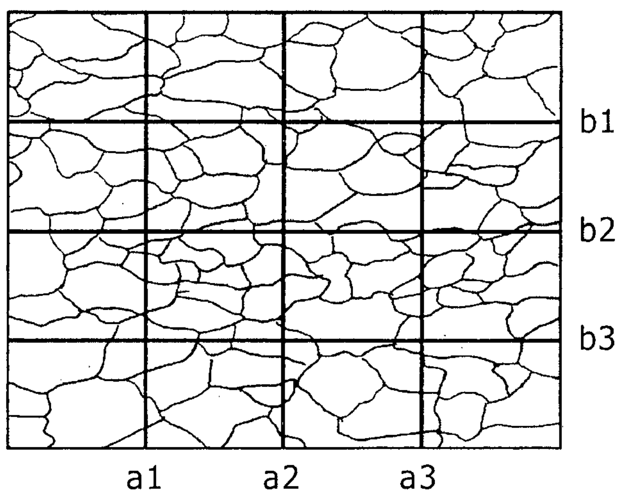

PRODUCT
OR
TEST SAMPLE
SAMPLE
POLISHING
RESIN

FIG. 3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EUROPEAN SEARCH REPORT

Application Number
EP 15 00 2832

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C22C
C22F

The present search report has been drawn up for all claims

3

Place of search	Date of completion of the search	Examiner
Munich	2 February 2016	González Junquera, J

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02-02-2016

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