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(54) ALUMINUM ALLOY SHEET FOR AUTOMOBILE STRUCTURAL MEMBER USE, AUTOMOBILE STRUCTURAL MEMBER, AND METHOD FOR PRODUCING ALUMINUM ALLOY SHEET FOR AUTOMOBILE STRUCTURAL MEMBER USE

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(57) ABSTRACT

Provided are: an aluminum alloy sheet for automobile structural member use having strength, formability, crushing properties, and corrosion resistance at excellent levels with balance; an automobile structural member; and a method for producing an aluminum alloy sheet for automobile structural member use. The aluminum alloy sheet for automobile structural member use is an Al—Mg—Si aluminum alloy sheet containing, in mass percent, 0.4% to 1.0% of Mg, 0.6% to 1.2% of Si, and less than 0.7% of Cu, with the remainder consisting of Al and impurities. The aluminum alloy sheet has an earing rate of −10.0% to −3.0%.

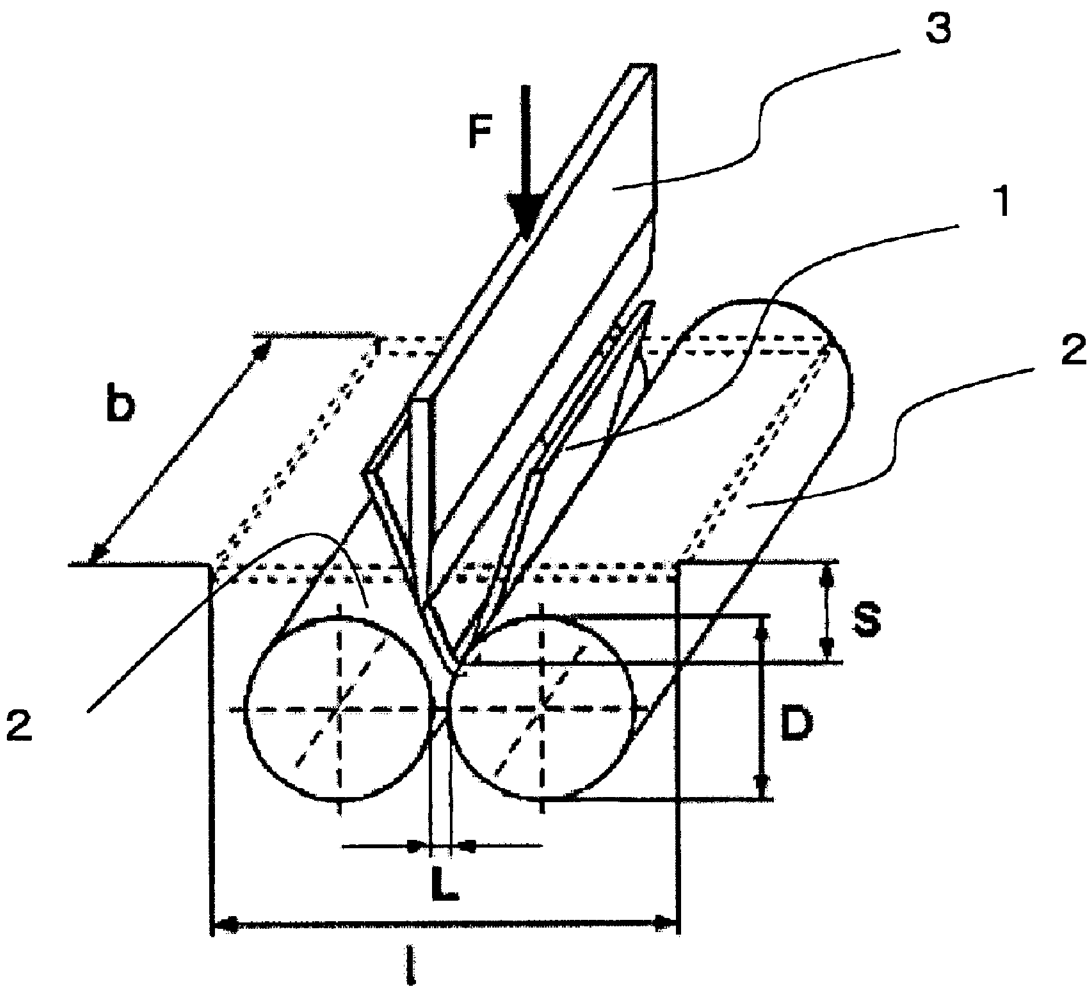


FIG. 1

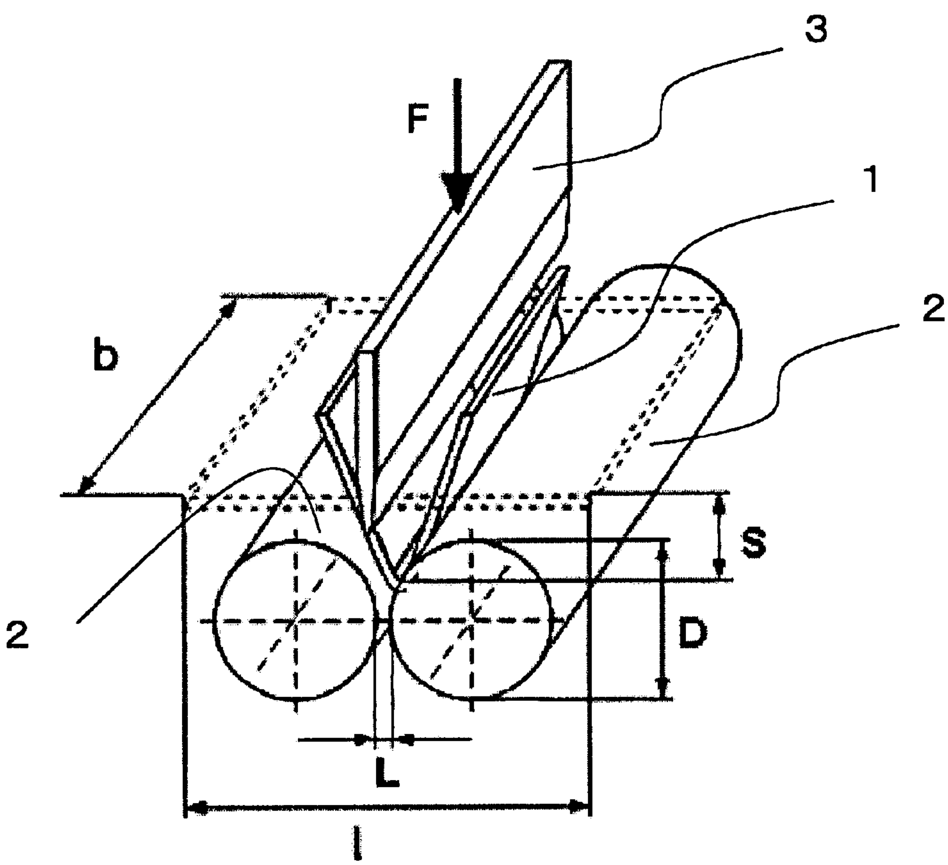


FIG. 2A

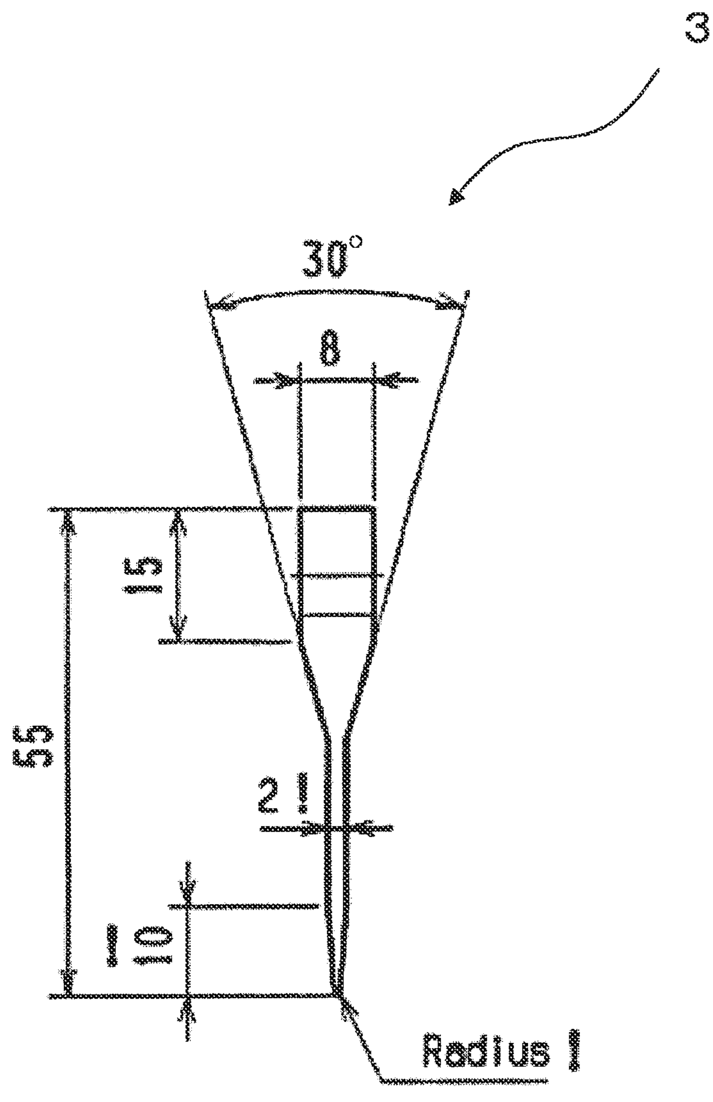
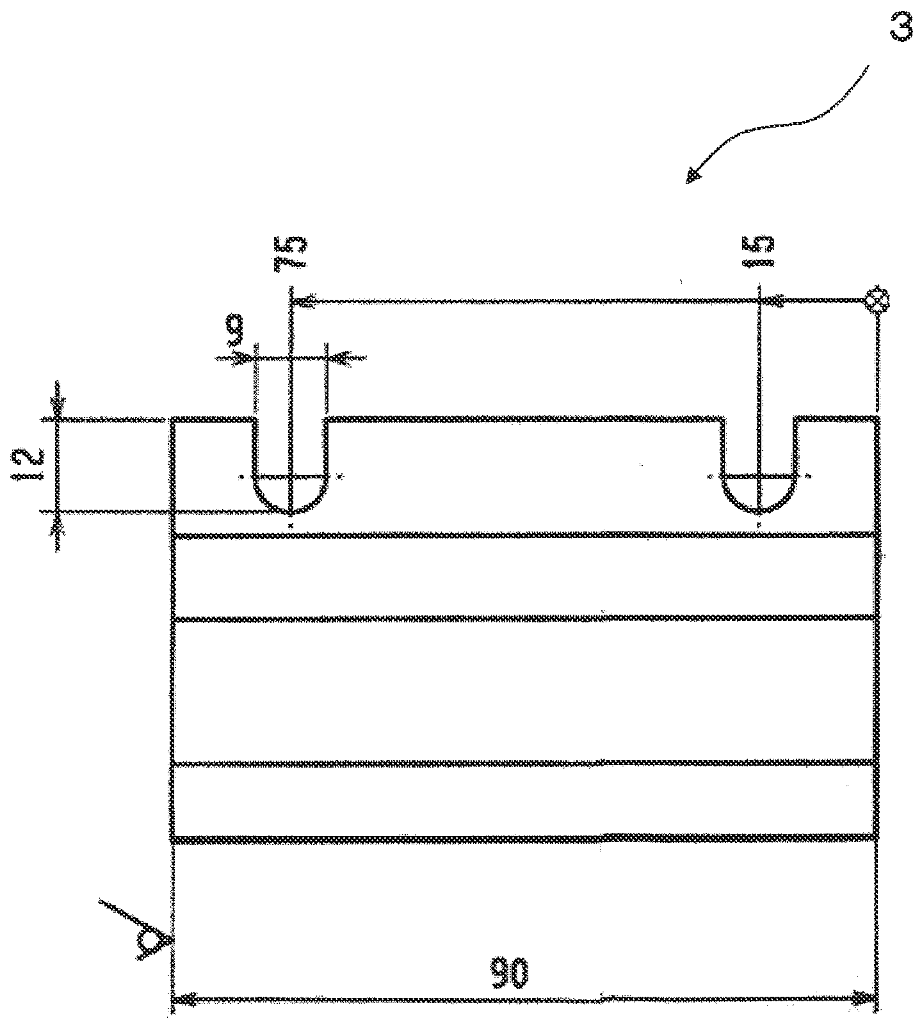


FIG. 2B



ALUMINUM ALLOY SHEET FOR AUTOMOBILE STRUCTURAL MEMBER USE, AUTOMOBILE STRUCTURAL MEMBER, AND METHOD FOR PRODUCING ALUMINUM ALLOY SHEET FOR AUTOMOBILE STRUCTURAL MEMBER USE

TECHNICAL FIELD

[0001] The present invention generally relates to Al—Mg—Si (6XXX-series) aluminum alloy sheets produced through regular rolling. In particular, the present invention relates to such an aluminum alloy sheet being used for automobile structural members and having excellent crushing properties.

[0002] As used herein, the term "aluminum alloy sheer" refers to a material aluminum alloy sheet which is a rolled sheet having undergone hot rolling and/or cold rolling, where the rolled sheet is after receiving tempering such as solution treatment and/or quenching, but before receiving forming into an automobile structural member and artificial aging such as paint bake hardening. In the following description, aluminum is also simply referred to as "Al".

BACKGROUND ART

[0003] Recent years have seen more and more increasing social needs for weight reduction of automobile bodies, in consideration typically of global environment. To adapt to such needs, aluminum alloy materials, instead of conventional ferrous materials such as steel sheets, are applied to panels (e.g., outer panels such as hoods, doors, and roofs, and inner panels) and reinforcements, such as bumper reinforcements (bumper R/Fs) and door beams, of the automobile bodies.

[0004] For further weight reduction of the automobile bodies, demands are made to apply such aluminum alloy materials also to side members and other members, frames, pillars, and other automobile structural members, because these members among automobile members, when reduced in weight, particularly contribute to weight reduction of automobile bodies. The automobile structural members have to be produced from aluminum alloy materials that have strength and formability equivalent to those for the automotive body panels and, in addition, have excellent impact absorption and crushing properties (crushing resistance or crushing characteristics) upon body collision, for the sake of passenger safety.

[0005] A non-limiting example of methods for measuring the crushing properties is "VDA 238-100 Plate bending test for metallic materials" (hereinafter also referred to as a "VDA bending test") standardized by German Association of the Automotive Industry (VDA). The VDA bending test has been employed in evaluation typically in Europe to meet the increased (stricter) level of automobile crash safety standards, and this requires frames, pillars, and other automobile structural members that have more excellent crushing characteristics.

[0006] Conventionally known ways to improve the crushing properties of 6XXX-series aluminum alloys for automobile structural member use include techniques of controlling the size or shape of grains, and the area fraction of Cube orientations. For example, Patent Literature (PTL) 1 discloses a 6XXX-series aluminum alloy sheet in which, of grains, the grain size in the through-thickness direction is specified, and the ratio of the grain size in the sheet rolling direction to the grain size in the through-thickness direction is controlled.

[0007] PTL 2 proposes a 6XXX-series aluminum alloy sheet in which the amounts of Mg, Si, and Cu are controlled, and the average area fraction of Cube orientations in a sheet cross section is controlled to be 22% or more. PTL 2, which has an objective to improve crushing properties, mentions that the VDA bending test as an evaluation test for sheet crushing properties has a correlation with crushing properties upon automobile collision. The VDA bending test gives a bending angle, which enables quantitative evaluation for the level of crushing properties of the sample.

CITATION LIST

Patent Literature

[0008] PTL 1: Japanese Unexamined Patent Application Publication (JP-A) No. 2001-294965

[0009] PTL 2: JP-A No. 2017-88906

SUMMARY OF INVENTION

Technical Problem

[0010] However, of such aluminum alloy sheets, the crushing properties are trade-off against the formability, and are also trade-off against the strength. For example, an aluminum alloy sheet, when produced by a production method regulated to provide better formability, has lower crushing properties. An aluminum alloy sheet, when produced from a material aluminum alloy having controlled metal contents to have higher strength, has lower crushing properties. As described above, safety standards typically for automobiles have become more and more strict, and this demands for aluminum alloy sheets that have such properties as to give higher safety. Accordingly, demands are made to develop aluminum alloy sheets having still better crushing properties without deterioration in strength and formability.

[0011] In addition, such automobile structural members require not only strength, formability, and crushing properties, but also corrosion resistance to corrosive environments such as salt water, from the viewpoint of reliability as structural members. Specifically, structural members derived from aluminum alloys require such excellent corrosion resistance as to resist grain-boundary corrosion and other corrosion over the long term.

[0012] Under these circumstance, the present invention has an object to provide: an aluminum alloy sheet for automobile structural member use, an automobile structural member, and a method for producing such an aluminum alloy sheet for automobile structural member use, where the aluminum alloy sheet is a 6XXX-series aluminum alloy sheet produced through regular rolling and excels in strength, formability, crushing properties, and corrosion resistance with balance as a material sheet.

Solution to Problem

[0013] After intensive investigations to achieve the object, the inventors of the present invention have found that an aluminum alloy sheet having strength, formability, crushing properties, and corrosion resistance at excellent levels with balance can be obtained by appropriately adjusting the chemical composition of the material aluminum alloy, defining the anisotropy of the aluminum alloy texture by earing rate, and controlling the earing rate within a predetermined range.

[0014] Specifically, the present invention provides an aluminum alloy sheet for automobile structural member use. The aluminum alloy sheet is an Al—Mg—Si aluminum alloy sheet containing, in mass percent, 0.4% to 1.0% of Mg, 0.6% to 1.2% of Si, and less than 0.7% of Cu, with the remainder consisting of Al and impurities. The aluminum alloy sheet has an earing rate of −10.0% to −3.0%.

[0015] Ina preferred embodiment of the present invention, the aluminum alloy sheet for automobile structural member use contains Mg in a content, in mass percent, of 0.4% to 0.6%. Ina preferred embodiment of the present invention, the aluminum alloy sheet for automobile structural member use contains Si in a content, in mass percent, of 0.6% to 0.8%. Ina preferred embodiment of the present invention, the aluminum alloy sheet for automobile structural member use has such bake hardenability as to have a 0.2% yield strength of 215 MPa or more after receiving artificial aging at a temperature of 180° C. for 20 minutes.

[0016] The present invention also provides an automobile structural member derived from any of the aluminum alloy sheets for automobile structural member use.

[0017] The present invention also provides a method for producing an aluminum alloy sheet for automobile structural member use. The method is a method for producing an Al—Mg—Si aluminum alloy sheet and includes the step of casting an aluminum alloy containing, in mass percent, 0.4% to 1.0% of Mg, 0.6% to 1.2% of Si, and less than 0.7% of Cu, with the remainder consisting of Al and impurities, to give an ingot. The ingot then receives homogenizing, hot rolling, cold rolling, annealing, solutionizing (solution treatment), and quenching. A rolling reduction in the cold rolling step is controlled to be 40% or more; and a heat treatment temperature in the annealing step is set to be 275° C. or higher.

Advantageous Effects of Invention

[0018] The present invention can provide an aluminum alloy sheet which is used for an automobile structural member and which has strength, formability, crushing properties, and corrosion resistance at excellent levels with balance, by appropriately regulating the chemical composition of the material aluminum alloy and allowing the aluminum alloy to have anisotropy in texture.

[0019] The present invention enables production of an aluminum alloy sheet for automobile structural member use, which aluminum alloy sheet excels in strength, formability, crushing properties, and corrosion resistance, and enables production of an automobile structural member from the aluminum alloy sheet, by adjusting the chemical composition of the material aluminum alloy and regulating the cold rolling reduction and the annealing heat treatment temperature in the production process.

BRIEF DESCRIPTION OF DRAWINGS

[0020] FIG. **1** is a perspective view of a system for a VDA bending test to evaluate crushing properties;

[0021] FIG. **2**A is a front view of the punch in FIG. **1**; and

[0022] FIG. **2**B is a side view of the punch in FIG. **1**.

DESCRIPTION OF EMBODIMENTS

[0023] Hereinafter detailed description will be made on reasons for specifying the chemical composition and the earing rate of an aluminum alloy sheet for automobile structural member use, and on reasons for specifying conditions and factors in a method for producing an aluminum alloy sheet for automobile structural member use, where the aluminum alloy sheet and the method are according to an embodiment of the present invention (the present embodiment).

[0024] The description will be made based on the premise that the Al—Mg—Si (hereinafter also referred to as "6XXX-series") aluminum alloy sheet according to the embodiment of the present invention is used not for automotive body panels as in conventional use, but for the automobile structural member or members.

[0025] The automobile structural member (hereinafter also simply referred to as "structural member") therefore requires to have not only formability as required of the conventional automotive body panels, but also excellent crushing properties and high yield strength even after artificial aging, where these properties are properties necessary particularly for the automobile structural members. A structural member, if lacking any of these properties, is insufficient as a structural member at which the present embodiment aims.

[0026] Accordingly, the requirements in the present embodiment as described below are signified to meet and balance among these specific demand properties to be used for the structural members.

[0027] As used in the present embodiment, the term "XX to YY" means that the factor in question is equal to or greater than the lower limit value (XX) and equal to or less than the upper limit value (YY).

[0028] Aluminum Alloy Sheet Chemical Composition

[0029] To provide the demand properties as the structural member, the Al—Mg—Si aluminum alloy sheet according to the present embodiment contains, in its chemical composition in mass percent, 0.4% to 1.0% of Mg, 0.6% to 1.2% of Si, and less than 0.7% of Cu, with the remainder consisting of Al and impurities.

[0030] The range, significance, or permissible level of the content of each element in the Al—Mg—Si aluminum alloy will be described below. All percentages in contents are by mass.

[0031] Mg content: 0.4% to 1.0%

[0032] Magnesium (Mg) forms, together with Si, Mg_2Si and other compound phases and precipitates upon artificial aging such as baking finish treatment. Thus, appropriate control of the Mg content allows the aluminum alloy sheet to have higher strength.

[0033] An aluminum alloy sheet having a Mg content of less than 0.4% may fail to have sufficient strength as a structural member.

[0034] In contrast, an aluminum alloy sheet having a Mg content of greater than 1.0% may undergo formation or precipitation of coarse particles of Mg_2Si and other compound phases upon casting and upon solutionization-quenching treatment, and the coarse particles will work as fine fracture origins. This causes the aluminum alloy sheet to have lower crushing properties. The Mg content is preferably 0.8% or less, and more preferably 0.6% or less.

[0035] The "strength of an aluminum alloy sheet" herein can be evaluated by a measured 0.2% yield strength (MPa) of the aluminum alloy sheet (before artificial aging) after solution treatment and quenching.

[0036] The strength can also be evaluated by a measured 0.2% yield strength of an aluminum alloy sheet (after artificial aging), where the aluminum alloy sheet (after artificial aging) is derived from the aluminum alloy sheet (before artificial aging) through the application of a prestrain of 2% or more and artificial aging at a temperature of 180° C. for 20 minutes.

[0037] The aluminum alloy sheet, when having a higher 0.2% yield strength (before artificial aging) and/or a higher 0.2% yield strength (after artificial aging), has higher strength and better bake hardenability (BH).

[0038] Si content: 0.6% to 1.2%

[0039] Silicon (Si) forms, together with Mg, Mg_2Si and other compound phases and precipitates upon artificial aging such as baking finish treatment. Thus, appropriate control of the Si content allows the aluminum alloy sheet to have higher strength.

[0040] An aluminum alloy sheet having a Si content of less than 0.6% may hardly provide sufficient strength as a structural member. The Si content is preferably 0.7% or more, and more preferably 0.8% or more.

[0041] In contrast, an aluminum alloy sheet having a Si content of greater than 1.2% may undergo formation or precipitation of coarse particles of Mg_2Si and other compound phases upon casting and upon solutionization-quenching treatment, and the coarse particles will work as fine fracture origins to cause the aluminum alloy sheet to have lower crushing properties. The Si content is preferably 1.1% or less, more preferably 1.0% or less, and still more preferably 0.8% or less.

[0042] Cu content: less than 0.7%

[0043] Copper (Cu), if present in a content of 0.7% or more, forms a precipitation free zone (also called PFZ) in the vicinity of a grain boundary as associated with aging precipitation, and the zone, which is less potentially noble than the inside of the grain, selectively dissolves in a corrosive environment and causes the aluminum alloy sheet to have lower resistance to grain-boundary corrosion (corrosion resistance).

[0044] To eliminate or minimize this, the Cu content is controlled to be less than 0.7%. The Cu content is preferably 0.5% or less, and more preferably 0.3% or less. The Cu content herein has no lower limit and may be 0%.

[0045] Other Elements

[0046] The other elements (such as elements described below) than the above-mentioned elements are basically regarded as impurities in the present embodiment. The contents of these elements are described below regarding their upper limits, which are permissible levels when being derived from melting materials, such as scrap, to form ingots. The contents have no lower limits and may be 0%.

[0047] Mn: 1.0% or less, Fe: 0.5% or less, Cr: 0.3% or less, Zr: 0.2% or less, V: 0.2% or less, Ti: 0.1% or less, Zn: 0.5% or less, Ag: 0.1% or less, and Sn: 0.15% or less.

[0048] These elements, when present in contents within the ranges, do not impair advantageous effects of the present invention, not only when contained as unavoidable impurities, but also when added willingly.

[0049] Aluminum Alloy Sheet Thickness: 1.5 mm or More

[0050] The thickness of the Al—Mg—Si aluminum alloy sheet according to the present embodiment is not limited in its lower limit, but is typically 1.5 mm or more, to provide strength and rigidity necessary as an automobile structural member. The thickness is also not limited in its upper limit, but is typically 4.0 mm or less, in consideration of limitations in forming such as press forming and the range of such allowable weight increase as not to adversely affect the weight reduction effect as compared with a steel sheet as a comparative material. Whether the material sheet having a thickness within the range is formed as a hot-rolled sheet or cold-rolled sheet is appropriately selected.

[0051] Earing Rate: −10.0% to −3.0%

[0052] The earing rate of an aluminum alloy sheet indicates texture anisotropy and shows a strong correlation particularly with the integration degree of Cube orientations. An aluminum alloy sheet having an earing rate of greater than −3.0% may include Cube orientations with a low integration degree, fail to restrain a shear zone in bending deformation during crushing, and have lower crushing properties.

[0053] In contrast, an aluminum alloy sheet having an earing rate of less than −10.0% may include Cube orientations excessively highly integrated and have a lower breaking elongation, namely, have lower formability, as a result of concentration of strain to the Cube orientations.

[0054] Earing Rate Measuring Method

[0055] From a test sample, a disk-shaped test specimen (blank) having an outer diameter of 66 mm is blanked, and the test specimen receives cupping using a 40-mm diameter punch to give a drawn cup having a cup diameter of 40 mm. The heights of ears of the drawn cup are measured, on the basis of which the earing rate (%) can be calculated according to Formula (1) below.

[0056] In Formula (1), hX represents the height of an ear of the drawn cup; and the index X of h represents the measurement position of the cup height (ear height), where the position is a position making an angle of X° with the sheet rolling direction of the aluminum alloy sheet.

$$\text{Earing rate (\%)}=[\{(h45+h135+h225+h315)-(h0+h90+h180+h270)\}/\{\tfrac{1}{2}(h0+h90+h180+h270+h45+h135+h225+h315)\}]\times 100 \quad (1)$$

[0057] For illustrating its significance, Formula (1) can also be expressed as Formula (2):

Earing rate (%)={((Average of heights at four points in the 45° direction relative to the bottom(the sheet rolling direction) of the cup)−(Average of heights at four points in the 0° and 90° directions relative to the bottom of the cup))/(Average of heights at eight points in the 0°,45°, and 90° directions relative to the bottom of the cup)}×100 (2)

[0058] Crushing Properties

[0059] As used herein, the term "crushing properties" refers to such properties that the resulting automobile structural member resists cracking and crushing and, even when undergoing cracking and/or crushing, deforms to the last in the early stages of and during deformation upon application of an impulsive load such as in automobile collision. A member having good crushing properties resists cracking and crushing and, even when undergoing cracking and/or crushing, undergoes bending deformation like an accordion.

[0060] As described above, the crushing properties may deteriorate when the material aluminum alloy has a Mg content and a Si content each greater than the upper limit of the range specified in the present embodiment. The crushing properties can be evaluated by the VDA bending test mentioned later. Regarding the crushing properties, the aluminum alloy sheet has a bending angle of preferably 93° or more, more preferably 100° or more, further more preferably 105° or more, and still more preferably 110° or more.

[0061] In the present embodiment, an aluminum alloy sheet having such crushing properties as to give a bending angle of 93° or more is evaluated as being accepted for automobile structural member use. In contrast, an aluminum alloy sheet having such crushing properties as to give a bending angle of less than 93° is evaluated to be insufficient for automobile structural member use.

[0062] A bending test to evaluate the crushing properties operates in accordance with the VDA bending test prescribed in German Association of the Automotive Industry (VDA).

[0063] FIG. **1** illustrates, as a perspective view, how to preform the bending test. FIG. **2**A and FIG. **2**B are a front view and a side view, respectively, of a punch **3**, which is a sheet-like bending jig.

[0064] Initially, two rollers **2** are disposed in parallel to each other with a roller gap L, and a sheet-like test specimen **1** is placed horizontally on the two rollers **2** equally in length on both sides, as indicated by the doted lines in FIG. **1**.

[0065] Next, the punch **3**, which is a sheet-like bending jig, is placed vertically above the sheet-like test specimen **1**. Specifically, the rollers **2**, the test specimen **1**, and the punch **3** stand so that the top edge side of the punch **3** lies at the center of the roller gap L, and the sheet rolling direction of the sheet-like test specimen **1** intersects with the extending direction of the sheet-like punch **3** at right angles.

[0066] The punch **3** then presses from above against the central part of the sheet-like test specimen **1** to put a load F on the test specimen, thereby bends the sheet-like test specimen **1** by pushing (by pressing) toward the narrow roller gap L, and presses the central part of the bent, deformed sheet-like test specimen **1** into the narrow roller gap.

[0067] In this process, a bending angle (in degree) at the time when the load F, which is put by the punch **3** from above, becomes maximum is measured, and the crushing properties are evaluated by the magnitude of the bending angle, where the bending angle is defined as the outer bending angle of the central part of the sheet-like test specimen **1**. It can be determined that, with an increasing bending angle, the sheet-like test specimen more remains in a bending deformation state without crushing during bending, and offers higher crushing properties.

[0068] The VDA bending test operates under conditions as follows. The sheet-like test specimen **1** has a thickness of 2.0 mm and has a square shape of a width b of 60 mm by a length l of 60 nm. The two rollers **2** each have a diameter D of 30 mm and lie with a roller gap L of 4.0 mm, which is 2.0 times as much as the thickness of the sheet-like test specimen **1**. At the time when the load F becomes maximum, the central part of the sheet-like test specimen presses into the roller gap at a depth S.

[0069] As illustrated in FIG. **2**B, the punch **3** has a length of a side in contact with the test specimen **1** of 90 mm, and has a tapered narrow shape so that its lower side (apex) has a radius r of 0.2 mm, where the lower side presses against the central part of the sheet-like test specimen **1**, as illustrated in the front view of the punch **3**.

[0070] The punch **3** has two recesses each having a width of 9 mm and a depth of 12 mm, in the opposite side to the apex. The punch **3** is configured to apply a load on the test specimen **1** when the recesses of the punch **3** are engaged to a loading device (not shown).

[0071] Strength

[0072] The aluminum alloy sheet according to the present embodiment, when receiving a prestrain of 2% or more and undergoes artificial aging at a temperature of 180° C. for 20 minutes after receiving solution treatment (solutionization) and quenching, preferably has a 0.2% yield strength (bake hardenability or BH) of 215 MPa or more.

[0073] The aluminum alloy sheet, when having a 0.2% yield strength of 215 MPa or more, can surely have strength necessary as an alloy sheet for automobile structural member use. The 0.2% yield strength can be controlled not only by the contents of elements in the aluminum alloy, but also particularly by the thermal hysteresis and the rolling reduction in in the steps in the after-mentioned production method.

[0074] Formability

[0075] An aluminum alloy sheet according to the present embodiment, if produced by a method with a rolling reduction in cold rolling lower than the lower limit of the range specified in the present embodiment, may have lower formability, as described later. The formability can be evaluated by breaking elongation as indicated in working examples below, and the aluminum alloy sheet preferably has such formability as to give a breaking elongation of 25% or more.

[0076] In the present embodiment, an aluminum alloy sheet having such formability as to give a breaking elongation of 25% or more is evaluated as being accepted for automobile structural member use. In contrast, an aluminum alloy sheet having such formability as to give a breaking elongation of less than 25% is evaluated as being insufficient for automobile structural member use.

[0077] Method for Producing Aluminum Alloy Sheet for Automobile Structural Member Use

[0078] Next, a method for producing the aluminum alloy sheet according to the present embodiment will be illustrated below.

[0079] The method for producing an aluminum alloy sheet for automobile structural member use according to the present embodiment is a method for producing an Al—Mg—Si aluminum alloy sheet. The method includes the steps of casting, homogenizing, hot rolling, cold rolling, annealing, solution-treating, and quenching, where the step of casting preforms on an aluminum alloy having the chemical composition. In the method, a rolling reduction in the cold rolling step is controlled to be 40% or more, and a heat treatment temperature in the annealing step is set to be 275° C. or higher.

[0080] The earing rate as specified in the present embodiment can be obtained by appropriately regulating, among these production steps, the rolling reduction in the cold rolling and the temperature in the annealing process within the numerical ranges. Each step or process will be illustrated in detail below.

[0081] Melting and Casting

[0082] Initially, in the melting-casting step, a molten aluminum alloy is prepared by melting to have a chemical composition within the range of the 6XXX-series chemical composition and is cast. The casting operates by a casting technique appropriately selected from regular melting-casting techniques such as continuous casting and semicontinuous casting (direct chill casting; DC casting).

[0083] Homogenization

[0084] Next, the cast aluminum alloy ingot receives homogenization prior to hot rolling. The homogenization (soaking) is significant not only for homogenization of the microstructure (elimination or minimization of segregation in grains in the ingot microstructure), which is a common objective, but also for sufficient solid-solution (solutionization) of Si and Mg. The homogenization may work under any conditions without limitation, as long as the homogenization can achieve the objects. The homogenization (soaking) may operate as common single or single-stage treatment.

[0085] The homogenization preferably operates at a temperature for a (holding) time appropriately selected within the ranges respectively from 500° C. to 560° C. and one hour or longer. The homogenization, if operating at an excessively low temperature, may fail to sufficiently eliminate segregation in grains, and the residual segregation will work as a fracture origin, and this may cause the aluminum alloy sheet to have lower crushing properties.

[0086] Hot Rolling

[0087] The hot rolling of the ingot after homogenization includes a rough rolling substep of the ingot (slab) and a finish rolling substep, in accordance with the target thickness after rolling. The hot rough rolling substep and hot finish rolling substep may employ any of rolling mills such as reverse mills and tandem mills as appropriate.

[0088] Rough Rolling Substep

[0089] Hot rolling in the hot rough rolling substep, if started at a start temperature higher than the solidus temperature, may cause burning, and this may impede the hot rolling itself. Hot rolling, if started at a start temperature lower than 350° C., may require an excessively high load to operate on any material after the homogenization step, and this may impede the hot rolling itself. To eliminate or minimize these, hot rolling operates at a hot rolling start temperature selected within the range from 350° C. to the solidus temperature, to give a hot-rolled sheet having a thickness of about 2 to about 8 mm. Annealing (heat treatment) of this hot-rolled sheet before cold rolling is not always necessary, but may be performed.

[0090] Hot Finish Rolling

[0091] After the hot rough rolling, hot finish rolling preferably operates to an end temperature from 250° C. to 350° C. The hot finish rolling, if operating to an excessively low end temperature lower than 250° C., may cause lower productivity due to a higher rolling load. In contrast, the hot finish rolling, if operating to an excessively high end temperature higher than 350° C. so as to give a recrystallized microstructure without a large amount of residual deformed microstructure, may highly possibly cause the aluminum alloy sheet to have lower crushing properties, due to precipitation of coarse Mg_2Si particles.

[0092] Annealing (heat treatment) of this hot-rolled sheet before cold rolling is not always necessary, but may be performed.

[0093] Cold Rolling

[0094] The step of cold rolling the hot rolled sheet to a desired thickness, when operating at a high cold rolling reduction, can introduce strain homogeneous in the through-thickness direction, and this will give homogeneous, fine, equiaxial grains upon the solution heat treatment. Specifically, cold rolling operating at a cold rolling reduction of 40% or more allows the texture to have such anisotropy as to give crushing properties and formability with balance. This can give an aluminum alloy sheet having an earing rate of −10.0% or more.

[0095] In contrast, cold rolling, if operating at a cold rolling reduction of less than 40%, may introduce little strain, and this may cause the deformed microstructure after hot rolling to remain. This may cause the aluminum alloy sheet to have an earing rate of less than −10.0%. The resulting aluminum alloy sheet may have better crushing properties, but significantly lower formability. To eliminate or minimize this, the cold rolling operates at a cold rolling reduction of 40% or more.

[0096] The cold rolling reduction is preferably 60% or more.

[0097] Annealing Process

[0098] An annealing process at a temperature of 275° C. or higher allows the nuclei of Cube orientations remained after cold rolling to preferentially grow without coarsening and gives an aluminum alloy sheet having an earing rate of −3.0% or less. As a result, the aluminum alloy sheet can have not only excellent formability as with conventional equivalents, but also satisfactory crushing properties. Annealing, if operating at a temperature of lower than 275° C., which is equal to or lower than the recrystallization temperature, may fail to invite recrystallization, to cause the aluminum alloy sheet to have an earing rate of greater than −3.0%, and to thereby have significantly lower crushing properties although having good formability.

[0099] The annealing temperature is preferably 300° C. or higher.

[0100] The annealing process preferably operates at a rate of temperature rise of 1 to 500° C./hr. The annealing process, if operating at a rate of temperature rise of less than PC/hr, may cause grains to coarsen and have larger sizes, and this may cause the aluminum alloy sheet to tend to have lower crushing properties. The annealing process, if operating at a rate of temperature rise of greater than 500° C./hr, may cause Cube orientation nuclei to be present in a small number, and this may cause the Cube orientations after solution treatment to be present in a smaller area fraction and cause the aluminum alloy sheet to tend to have lower crushing properties.

[0101] Solution Treatment and Quenching

[0102] After the cold rolling, the workpiece receives a solution treatment, and subsequent quenching down to room temperature. The solution treatment and quenching may preform using a common continuous heat treatment line. However, for sufficient amounts of solid-solutions of the elements such as Mg and Si, it is preferred that the workpiece receives the solution treatment at a temperature from 500° C. to the melting temperature, and then receives quenching down to room temperature at an average cooling rate of 20° C./sec or more. The workpiece, if receiving a solution treatment at a temperature lower than 500° C., may include smaller amounts of solute Mg and solute Si, because Mg—Si compounds and other compounds formed before the solution treatment undergo re-solutionization insufficiently.

[0103] The workpiece, if receiving quenching at an average cooling rate of less than 20° C./sec, may highly possibly fail to include sufficient amounts of solute Si and solute Mg, because Mg—Si precipitates predominantly form during cooling, and this lowers the amounts of solute Mg and solute Si. To surely provide a cooling rate within the range, the quenching operates with a selective means under selective conditions, where non-limiting examples of the means include air cooling means such as fans; and water cooling means such as mist, spraying, and immersion. After the solution treatment as above, the workpiece may receive pre-aging as appropriate.

Automobile Structural Member

[0104] The present embodiment also relates to an automobile structural member made from the aluminum alloy sheet. The aluminum alloy sheet according to the present embodiment has strength, formability, and crushing properties at excellent levels with balance as a material sheet, and can give an automobile structural member having still better safety.

[0105] The present invention will be illustrated in further detail with reference to several examples below. It should be noted, however, that the examples are by no means intended to limit the scope of the invention that various changes and modifications can naturally be made therein as appropriate without deviating from the spirit and scope of the invention as described herein; and that all such changes and modifications should be considered to be within the scope of the invention.

Examples

[0106] Ingots of 6XXX-series aluminum alloys having the chemical compositions given in Table 1 were prepared, from which aluminum alloy sheets for automobile structural member use were produced under various production conditions given in Table 2, and received earing rate measurement.

[0107] The produced aluminum alloy sheets were evaluated for strength, formability, and crushing properties by measurements of the 0.2% yield strength (MPa) before and after artificial aging, the breaking elongation (%), and the VDA bending angle (degree) after artificial aging. The results are also presented in Table 2.

[0108] Aluminum Alloy Sheet Production

[0109] Initially, production conditions will be described in detail. Aluminum alloys having the chemical compositions given in Table 1 were molten and cast to give ingots. The ingots received a homogenization treatment by holding the same at a temperature of 540° C. for 4 hours. The ingots then received hot rolling to an end temperature of 250° C. to 350° C. The workpieces further received cold rolling at the rolling reductions given in Table 2 to a final thickness of 2.0 mm, and yielded cold-rolled sheets.

[0110] The cold-rolled sheets received an annealing process in an air furnace, in which each workpiece was raised in temperature at a rate of 30° C./hr, held at the annealing temperature given in Table 2 for 4 hours, and cooled down at a rate of 40° C./hr. However, the workpiece according to Comparative Example 1 did not receive the annealing process.

[0111] The workpieces then received a tempering treatment (T4 treatment) under common conditions in a heat treatment facility. Specifically, each sheet after the annealing was heated at an average heating rate up to the solution treatment temperature of 5° C./sec, held at a temperature of 525° C. for 28 seconds for the solution treatment, and then cooled down to room temperature by fan air cooling at an average cooling rate of 20° C./sec. Immediately after the cooling, the workpieces received pre-aging by holding the same at 80° C. for 5 hours, and then received slow cooling (natural cooling) and yielded a series of aluminum alloy sheets (T4 sheets).

[0112] Earing Rate Measurement

[0113] From the produced aluminum alloy sheets, test samples were sampled, and received earing rate measurement by the following method. A disk-shaped test specimen having an outer diameter of 66 mm was blanked from each test sample, and the test specimen received cupping using a punch having a diameter of 40 mm and yielded a drawn cup having a cup diameter of 40 mm. The ear heights of the drawn cup were measured, from which the earing rate (%) was calculated according to Formula (1).

[0114] Strength Evaluation: 0.2% Yield Strength Measurement

[0115] From each test sample, a JIS 13A tensile test specimen (20 mm by 80 mm gauge length by 2.0 mm) was sampled, and received a tensile test at room temperature under the following conditions, to measure the 0.2% yield strength. Initially, two sets of test samples after pre-aging were prepared, and one of the two was subjected to a 0.2% yield strength measurement without additional heat treatment. The other set received a prestrain of 2% or more, and underwent artificial aging at a temperature of 180° C. for 20 minutes and subsequent measurement of 0.2% yield strength.

[0116] The tensile test operated so that the tensile direction be perpendicular to the sheet rolling direction.

[0117] The tensile speed was set at 5 mm/min before the load reached the 0.2% yield strength, and set at 20 mm/min on or above the 0.2% yield strength. The measurement operated five times, the five measurements were averaged, and the average was defined as the 0.2% yield strength. A sample having a 0.2% yield strength of 215 MPa or more after artificial aging was determined as having sufficient strength for automobile structural member use and evaluated as accepted.

[0118] Formability Evaluation: Breaking Elongation Measurement

[0119] From each test sample, a JIS 13A tensile test specimen (20 mm by 80 mm gauge length by 2.0 nm) was sampled, and received a tensile test at room temperature under the following conditions. In the tensile test using a tensile tester, the test specimen was pulled at a speed of 5 mm/min, and the elongation at the time when the test specimen broken (ruptured) was measured.

[0120] The test specimen was pulled in three directions, i.e., 0° direction, 45° direction, and 90° direction relative to the sheet rolling direction, and received the measurement five times, from which five breaking elongations were calculated according to Formula (3) below and averaged, and the average was defined as the breaking elongation of the sample. In Formula (3), Lo represents the gauge length before the tensile test and L represents the gauge length at break.

$$\text{Breaking elongation }(\%)=100\times(L-Lo)/Lo \tag{3}$$

[0121] A sample having a breaking elongation of 25% or more was determined as having sufficient formability for automobile structural member use and evaluated as accepted.

[0122] Crushing Properties Evaluation: VDA Bending Angle Measurement

[0123] The test sample after the preliminary treatment received a prestrain of 2% or more and underwent artificial aging at a temperature of 180° C. for 20 minutes. From the resulting sample, a square test specimen having a thickness of 2.0 mm, a width b of 60 mm, and a length l of 60 mm was sampled, and received a VDA bending test to evaluate crushing properties.

[0124] The VDA bending test operated in conformity to VDA 238-100 as a three-point bending test so that the bend line be in parallel with the sheet rolling direction. In the test, the bending speed was set at 10 mm/min until the load reached 30 N, and set at 20 mm/min thereafter. The system was set so that bending was stopped at the time when cracking occurred or the load decreased from the maximum load by 60 N due to reduction in sheet thickness.

[0125] The bending test operated on three test specimens per sample, the three measurements were averaged, and the average was defined as the bending angle (degree) of the sample.

[0126] A sample having a bending angle of 93° or more was determined as having sufficient crushing properties for automobile structural member use and evaluated as accepted.

TABLE 1

Alloy	Chemical composition (mass percent, the remainder consisting of Al and unavoidable impurities)		
number	Mg	Si	Cu
1	0.4	1.0	0.2
2	0.4	0.4	0.2
3	0.4	0.6	0.2
4	0.4	0.8	0.2
5	0.4	1.2	0.2
6	0.4	1.4	0.2
7	0.2	1.0	0.2
8	0.6	1.0	0.2
9	1.0	1.0	0.2
10	1.2	1.0	0.2
11	0.4	1.0	0.7

TABLE 2

		Content of element (the remainder consisting of Al and unavoidable impurities)			Aluminum alloy sheet production conditions			Evaluation results			
					Rolling reduction	Annealing	Material texture	Strength		Formability	Crushing properties
								0.2% Yield strength	0.2% Yield strength		
Category	Alloy number	Mg (mass percent)	Si (mass percent)	Cu (mass percent)	in cold rolling (%)	temper-ature (° C.)	Earing rate (%)	before arti-ficial aging (Mpa)	after arti-ficial aging (Mpa)	Breaking elongation (%)	VDA bending angle (°)
Example 1	1	0.4	1.0	0.2	60	300	−5.2	99	218	25	99
Example 2	1	0.4	1.0	0.2	60	350	−4.7	99	217	26	104
Example 3	1	0.4	1.0	0.2	60	400	−5.0	98	215	26	105
Example 4	1	0.4	1.0	0.2	80	350	−3.6	100	215	29	99
Example 5	3	0.4	0.6	0.2	60	350	−5.0	101	216	26	112
Example 6	4	0.4	0.8	0.2	60	350	4.9	104	220	26	106
Example 7	5	0.4	1.2	0.2	60	350	−4.8	110	229	27	99
Example 8	8	0.6	1.0	0.2	60	350	−4.9	100	219	27	101
Example 9	9	1.0	1.0	0.2	60	350	−5.1	101	222	27	96
Com. Ex. 1	1	0.4	1.0	0.2	60	なし	−1.9	101	220	27	83
Com. Ex. 2	1	0.4	1.0	0.2	60	200	−2.3	100	219	27	80
Com. Ex. 3	1	0.4	1.0	0.2	60	250	−2.3	103	221	27	87
Com. Ex. 4	1	0.4	1.0	0.2	0	350	−12.3	101	216	16	139
Com. Ex. 5	1	0.4	1.0	0.2	10	350	−12.0	102	215	17	140
Com. Ex. 6	1	0.4	1.0	0.2	30	350	−11.6	100	217	20	125
Com. Ex. 7	2	0.4	0.4	0.2	60	350	−5.8	95	208	25	116
Com. Ex. 8	6	0.4	1.4	0.2	60	350	−4.4	121	235	28	89
Com. Ex. 9	7	0.2	1.0	0.2	60	350	−5.6	95	207	26	109
Com. Ex. 10	10	1.2	1.0	0.2	60	350	−4.5	110	234	27	90

[0127] The evaluation results for the strength, formability, and crushing properties are presented in Table 2. In Table 2, a component content, a production condition for the aluminum alloy sheet, and a material microstructure each of which does not meet or fall within the range specified in the present invention are underlined.

[0128] Likewise, an evaluation result for the strength, formability, and crushing properties which result was not evaluated as accepted for automobile structural member use is underlined.

[0129] As apparent from Table 2, Examples 1 to 9 were produced from aluminum alloys having chemical compositions within the range specified in the present invention, where the production operated under conditions specified in the present invention.

[0130] Specifically, Examples 1 to 9 are samples produced from aluminum alloys having chemical compositions containing, in mass percent, 0.4% to 1.0% of Mg and 0.6% to 1.2% of Si, and had an earing rate of −10.0% to −3.0%. Thus, these samples were aluminum alloy sheets having strength, formability, and crushing properties at excellent levels with balance.

[0131] Comparisons are made among Example 2 (Mg content: 0.4%), Example 8 (Mg content: 0.6%), and Example 9 (Mg content: 1.0%), whose conditions are common except for the Mg content. The comparisons demonstrate that the samples having a Mg content from 0.4% to 0.6% have particularly excellent crushing properties.

[0132] Also, comparisons are made among Example 5 (Si content: 0.6%), Example 6 (Si content: 0.8%), Example 2 (Si content: 1.0%), and Example 7 (Si content: 1.2%), whose conditions are common except for the Si content. The comparisons demonstrate that the samples having a Si content from 0.6% to 0.8% have particularly excellent crushing properties.

[0133] In contrast, Comparative Examples 1 to 10 are samples produced using aluminum alloys having chemical compositions out of the range specified in the present invention, or samples produced through cold rolling at a rolling reduction out of the range specified in the present invention or through annealing at a temperature out of the range specified in the present invention, although the samples are produced from aluminum alloys having chemical compositions within the range specified in the present invention. As a result, these samples are inferior in 0.2% yield strength after artificial aging or in crushing properties.

[0134] More specifically, Comparative Example 1 did not receive the annealing process, thereby had an earing rate out of the range specified in the present invention, and had poor crushing properties. Comparative Examples 2 and 3 received annealing at a temperature lower than the range specified in the present invention, thereby had an earing rate out of the range specified in the present invention, and had poor crushing properties.

[0135] Comparative Examples 4 to 6 received cold rolling at a rolling reduction less than the range specified in the present invention, thereby had an earing rate out of the range specified in the present invention, and had poor formability.

[0136] Comparative Example 7 was produced from an aluminum alloy having a Si content less than the range specified in the present invention, and thereby had low strength.

[0137] Comparative Example 8 was produced from an aluminum alloy having a Si content greater than the range specified in the present invention and had poor crushing properties.

[0138] Comparative Example 9 was produced from an aluminum alloy having a Mg content less than the range specified in the present invention and had low strength.

[0139] Comparative Example 10 was produced from an aluminum alloy having a Mg content greater than the range specified in the present invention and had poor crushing properties.

[0140] Next, ingots of the aluminum alloys of alloy numbers 1 and 11 in Table 1 were prepared, from which aluminum alloy sheets for automobile structural member use were produced under production conditions as described in the Aluminum Alloy Sheet Production, except for the rolling reduction in cold rolling and the annealing temperature as given in Table 3. The aluminum alloy sheets were then evaluated for resistance to grain-boundary corrosion (corrosion resistance).

[0141] Grain-Boundary Corrosion Resistance Evaluation

[0142] The resistance to grain-boundary corrosion was evaluated by a test in conformity to ISO 11846, Method B. The test samples used herein were sheet test samples after the solution treatment. To remove a surface film, the test samples were immersed in a 5% NaOH (60° C.) for one minute, rinsed, immersed in 70% HNO_3 for one minute, rinsed again, and dried at room temperature.

[0143] An aqueous solution containing HCl and NaCl (containing 30 g/L of NaCl and 10±1 mL/L of 36% concentrated hydrochloric acid) was prepared as an etchant, and the test samples were immersed in the etchant at 25° C. for 24 hours, where the etchant was present in an amount of 5 ml per 1 cm^2 of the surface area of the material. Next, the test samples were immersed in 70% HNO_3 and brushed with a plastic brush to remove corrosion products, rinsed, and dried at room temperature.

[0144] Next, according to the focal depth method, portions (each 30 mm by 50 mm) which were determined to have deep corrosion were selected at three arbitrary points in each test sample, and the three portions were embedded and ground to give cross sections. The depth of deepest grain-boundary corrosion in each cross section was measured using an optical microscope. In this testing example, samples having a maximum grain-boundary corrosion depth of 300 μm or less were evaluated as accepted.

[0145] The evaluation results for resistance to grain-boundary corrosion are presented in Table 3. In the element contents in Table 3, data out of the range specified in the present invention are underlined.

[0146] Likewise, an evaluation result for the resistance to grain-boundary corrosion not evaluated as accepted is also underlined.

TABLE 3

Category	Alloy number	Content of element (the remainder consisting of Al and unavoidable impurities) Mg (mass percent)	Si (mass percent)	Cu (mass percent)	Aluminum alloy sheet production conditions: Rolling reduction in cold rolling (%)	Annealing temperature (° C.)	Grain-boundary corrosion resistance Maximum depth (μm)
Example 1	1	0.4	1.0	0.2	60	300	259
Com. Ex. 11	11	0.4	1.0	0.7			305

[0147] As indicated in Table 3, Example 1 was produced from an aluminum alloy having a Cu content within the range specified in the present invention and had excellent resistance to grain-boundary corrosion.

[0148] In contrast, Comparative Example 11 was produced from an aluminum alloy having a Cu content greater than the range specified in the present invention and had poor resistance to grain-boundary corrosion.

[0149] The results of the examples and the comparative examples demonstrate that aluminum alloy sheets meeting all the conditions for the chemical composition and for the microstructure specified in the present invention are advantageously usable for automobile structural members.

[0150] Various embodiments have been described above with reference to the attached drawings. It is naturally understood, however, that these embodiments are not construed to limit the scope of the present invention. It is apparent that a person skilled in the art could have conceived various variations and modifications within the spirit and scope of the invention as claimed in the appended claims, and it is naturally understood that all such variations and modifications should be considered to be within the scope of the invention. Any components or constituents in the embodiments may optionally be combined without departing from the spirit and scope of the invention.

[0151] This application claims priority to Japanese Patent Application No. 2018-070252, filed on Mar. 30, 2018, the entire contents of which application are incorporated herein by reference.

INDUSTRIAL APPLICABILITY

[0152] The present invention allows a 6XXX-series aluminum alloy sheet produced through regular rolling to combine excellent crushing properties and strength, which are properties specific to automobile structural member use, with formability and corrosion resistance. This enlarges the applicability of such 6XXX-series aluminum alloy sheets as automobile structural members.

REFERENCE SIGNS LIST

[0153] **1** sheet-like test specimen

[0154] **2** roller

[0155] **3** punch

1. An aluminum alloy sheet, the aluminum alloy sheet being an Al—Mg—Si aluminum alloy sheet comprising, in mass percent:

0.4% to 1.0% of Mg;

0.6% to 1, 2% of Si; and

less than 0.7% of Cu,

wherein the aluminum alloy sheet has an earing rate of −10.0% to −3.0%.

2. The aluminum alloy sheet of claim **1**,

wherein the aluminum alloy sheet comprises, in mass percent, 0.4% to 0.6% of Mg.

3. The aluminum alloy sheet of claim **1**,

wherein the aluminum alloy sheet comprises, in mass percent, 0.6% to 0.8% of Si.

4. The aluminum alloy sheet of claim **1**,

wherein the aluminum alloy sheet has a bake hardenability so as to have a 0.2% yield strength of 215 MPa or more after being subjected to artificial aging at a temperature of 180° C. for 20 minutes.

5. An automobile structural member, derived from the aluminum alloy sheet of claim **1**.

6. A method for producing an aluminum alloy sheet, the aluminum alloy sheet being an Al—Mg—Si aluminum alloy sheet, the method comprising:

casting;

homogenizing;

hot rolling;

cold rolling;

annealing;

solutionizing; and

quenching,

the casting being performed on an aluminum alloy comprising, in mass percent:

0.4% to 1.0% of Mg;

0.6% to 1.2% of Si; and

less than 0.7% of Cu,

wherein the cold rolling is performed to a cold rolling reduction of 40% or more, and

wherein the annealing is performed at a heat treatment temperature of 275° C. or higher.

* * * * *