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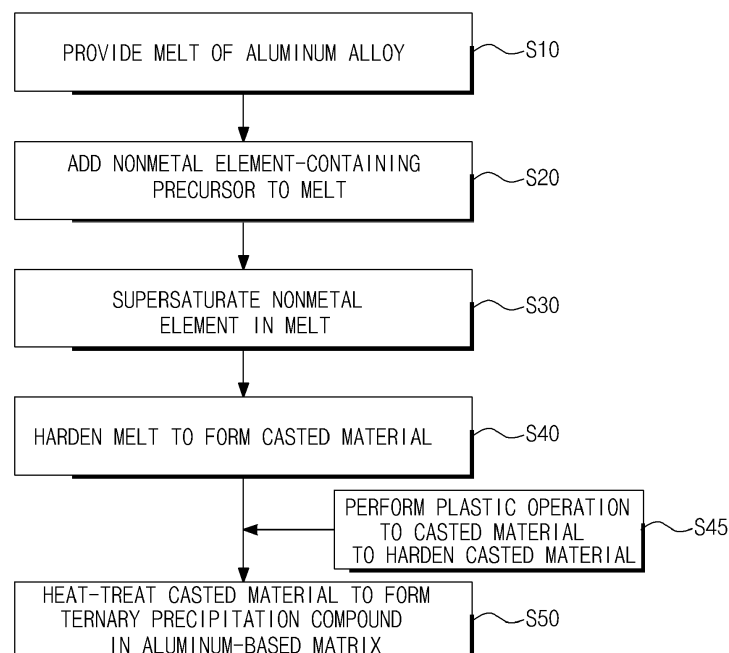
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(54) **ENGINEERED ALUMINUM ALLOY AND METHOD OF FABRICATING THE SAME**

(57) Provided are an aluminum alloy having an adjusted microstructure in an aluminum matrix or an aluminum alloy matrix for high elongation ratio or high strength and a method of fabricating the same. The aluminum alloy includes an aluminum-based matrix; and a precip-

itation compound dispersed in the aluminum-based matrix. The precipitation compound comprises a compound containing aluminum, one or more transition metals, and one or more non-metallic elements.

FIG. 4



Description**CROSS-REFERENCE TO RELATED APPLICATION**

[0001] This application claims the benefit of Korean Patent Applications No. 10-2016-0183446, filed on December 30, 2016 in the Korean Intellectual Property Office, the disclosure of which is incorporated herein in its entirety by reference.

BACKGROUND OF THE INVENTION

1. Field

[0002] The present disclosure relates to a metal material, and more particularly, to aluminum that is adjusted to have high strength and a method for fabricating the same.

2. Description of the Related Art

[0003] Generally, aluminum or its alloy is a material having a wide range of industrial applications because it may be fabricated in various shapes due to lightweight and durable characteristics of aluminum. Aluminum itself is easily deformed due to its low strength, but an aluminum alloy has high strength and high reliability due to elements added thereto to the extent that it may be applied to the automobile or aircraft industry. Recently, due to their excellent mechanical strengths and lightweights, aluminum alloys have been applied to various technologies, such as architecture, chemistry, robots, and electronic products, as well as automobiles and aircrafts.

[0004] As such, high-strength aluminum has been actively researched for development of components used in the fields of automobiles, bicycles, electric or electronics, or robots. Generally, as the number of kinds of elements added to an aluminum matrix of the aluminum alloy increases, improvements of strength and corrosion resistance may be expected, but elongation performance of the aluminum alloy for improving the workability of aluminum-based material may not improve or may be rather reduced.

[0005] Furthermore, in order to improve mechanical strength of pure aluminum having a low strength, it is generally preferable to form an aluminum alloy with an element, such as silicon (Si), magnesium (Mg), copper (Cu), manganese (Mn). Solid solution of these elements in an aluminum-based matrix or precipitation of a compound or a second phase precipitation may improve strength of the aluminum alloy. The aluminum alloy may be classified into a non-heat-treated alloy and a heat-treated alloy depending on whether it is hardened via a heat treatment. The non-heat-treated alloy may be improved in strength by strengthening by a second phase or a compound based on an alloying element, such as silicon, magnesium, or manganese, as described above. Examples of the non-heat-treated alloys include Al-Si alloys, Al-Mg alloys, and Al-Mn alloys.

[0006] The strength of the heat-treated alloy may be determined depending on the kind of alloying elements. For example, in an aluminum alloy to which copper (Cu) or zinc (Zn) is added, solid solubility of the added element increases as the temperature rises, and may be hardened by formation of precipitates via an aging treatment. The heat-treated alloys include Al-Cu alloys, Al-Zn alloys, and Al-Mg-Si alloys. However, in the case of the above-stated heat-treated alloy, since it is necessary to take castability or brittleness into account, the alloying elements may be limited. An aluminum alloys, which is strengthened by formation of a precipitate as a metallic compound by adding a heterogeneous metal element to aluminum may be expected to exhibit enhanced strength as compared to conventional heat-treated alloys.

SUMMARY OF THE INVENTION

[0007] Provided is an aluminum alloy capable of improving the strength of the aluminum alloy by forming a new reaction compound in the aluminum alloy for providing an efficient strengthening mechanism of the aluminum alloy.

[0008] According to an aspect of an embodiment, an aluminum alloy includes an aluminum-based matrix; and a precipitation compound dispersed in the aluminum-based matrix. The precipitation compound may include a compound containing aluminum, one or more transition metals, and one or more non-metallic elements.

[0009] In an example, an average size of the precipitation compound may be from about 10 nm to about 1 μ m. The transition metal may include at least one of chromium (Cr), iron (Fe), and manganese (Mn).

[0010] In an example, the non-metallic element may be supersaturated in the aluminum alloy and includes at least one of oxygen, nitrogen, and carbon. The precipitation compound may be formed via a heat treatment.

[0011] The aluminum-based matrix may include an aluminum alloy which comprises at least one of silicon (Si), zinc (Zn), magnesium (Mg), and copper (Cu). In an embodiment, the aluminum alloy may be work hardened by plasticity.

[0012] According to an aspect of another embodiment, a method of fabricating an aluminum alloy, the method includes providing a melt of an aluminum alloy comprising aluminum and a first transition metal; adding a non-metallic element-

containing precursor comprising at least one of a first reaction compound between the first transition metal and a non-metallic element, a second reaction compound between a second transition metal different from the first transition metal and the non-metallic element, and a third reaction compound between a non-transition metal and the non-metallic element to the melt; supersaturating the non-metallic element in the melt by decomposing the non-metallic element-containing precursor in the melt; forming a casted material by solidifying the melt; and forming a precipitation compound between aluminum, a transition metal, and a non-metallic element dispersed in an aluminum-based matrix by heat-treating the solidified casted material.

[0013] Furthermore, the first transition metal may include at least one of chromium (Cr), iron (Fe), and manganese (Mn). The non-metallic element may include at least one of oxygen, nitrogen, and carbon.

[0014] In an example, the non-transition metal of the third reaction compound may include at least one of aluminum (Al), silicon (Si), magnesium (Mg), and tungsten (W). The non-metallic element-containing precursor may be added to the melt in the form of power having the average diameter within a range from about 5 nm to about 50 nm.

[0015] The non-metallic element-containing precursor may be added in the range from 0.01 wt% to 5.0 wt% of the total weight of the melt. Furthermore, the method may further include plastic working and hardening the solidified casted material before the solidified casted material is heat treated. The heat treatment may be performed at a temperature within a range from 120 to 600 .

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] These and/or other aspects will become apparent and more readily appreciated from the following description of the embodiments, taken in conjunction with the accompanying drawings in which:

FIGS. 1A and 1B are transmission electron microscope (TEM) analysis images showing the microstructure of an aluminum alloy according to an embodiment of the present disclosure;

FIG. 2 is a graph showing a result of X-ray diffraction analysis for measuring stacking fault energy (SFE) of an aluminum alloy having a twin boundary or partial dislocation according to an embodiment of the present disclosure; FIGS. 3A through 3C are stress-deformation graphs showing results of measurement of elongation ratio of aluminum alloys having different compositions according to an embodiment of the present disclosure;

FIG. 4 is a flowchart of a method of fabricating an aluminum alloy according to an embodiment of the present disclosure;

FIGS. 5A and 5B are transmission electron microscope images showing precipitation compounds in an aluminum-based matrix formed by heat treatment according to an embodiment of the present disclosure, and FIG. 5C is a graph showing ingredients of the precipitation compounds analyzed via an energy dispersive X-ray spectroscopy (EDS);

FIG. 6 is a scanning electron microscope image showing a cross-sectional microstructure of an aluminum alloy casted material supersaturated with a non-metal element before heat treatment, according to a comparative embodiment;

FIG. 7 is a graph showing results of measuring tensile strength of an aluminum alloy according to an embodiment of the present disclosure and tensile strength of an aluminum alloy according to a comparative embodiment;

FIGS. 8A and 8B are graphs showing increases of tensile strength and strength of aluminum alloys according to various compositions of a precipitation compound according to an embodiment of the present disclosure, respectively; FIG. 9 is a graph showing results of measuring tensile strength of an aluminum alloy including a precipitation compound according to another embodiment and an aluminum alloy according to a comparative embodiment;

FIG. 10 is a graph showing results of measuring tensile strength of an aluminum alloy (solid line curve) including a precipitation compound according to another embodiment and an aluminum alloy according to a comparative embodiment.

DETAILED DESCRIPTION OF THE INVENTION

[0017] Reference will now be made in detail to embodiments, examples of which are illustrated in the accompanying drawings, wherein like reference numerals refer to like elements throughout. In this regard, the present embodiments may have different forms and should not be construed as being limited to the descriptions set forth herein. Accordingly, the embodiments are merely described below, by referring to the figures, to explain aspects.

[0018] In the drawings, for example, sizes and shapes of the members may be exaggerated for convenience and clarity of explanation. In addition, reference numerals of members in the drawings refer to the same members throughout the drawings. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items

[0019] The terms used in the present specification are merely used to describe particular embodiments, and are not

intended to limit the present disclosure. An expression used in the singular encompasses the expression of the plural, unless it has a clearly different meaning in the context. In the present specification, it is to be understood that the terms such as "including" or "having," etc., are intended to indicate the existence of the features, numbers, steps, actions, components, parts, or combinations thereof disclosed in the specification, and are not intended to preclude the possibility that one or more other features, numbers, steps, actions, components, parts, or combinations thereof may exist or may be added.

[0020] An aluminum alloy according to an embodiment of the present disclosure has a structure in which a non-metallic element may be solidified in an aluminum-based matrix. The aluminum-based matrix refers to a matrix formed of pure aluminum or an aluminum alloy. In the aluminum alloy, a result of X-ray diffraction analysis in which no peak related to a compound due to a reaction between aluminum and the non-metallic element is shown other than a peak related to the crystalline phase of aluminum supports that, in the aluminum alloy, the non-metallic element is a solid solution solidified in the aluminum-based matrix. The fact has been confirmed through X-ray diffraction analysis (XRD) and X-ray photoelectron spectroscopy (XPS) over a wide area of a fabricated aluminum-based matrix and, as shown in the XRD result of FIG. 2 (refer to the curve As-cast), only a pure aluminum crystal structure was detected.

[0021] The non-metallic element may include at least one of oxygen and nitrogen. The non-metallic element may be solidified to an amount of 1 wt% or less of the amount of aluminum. When the amount of the non-metallic element exceeds 1 wt% of aluminum, oxidation of the aluminum alloy occurs at a high priority, and thus it becomes difficult to harden the aluminum alloy. As a result, the elongation ratio of the aluminum alloy decreases.

[0022] The aluminum alloy may include a heterogeneous metal element other than aluminum. The heterogeneous metal element may include at least one of copper, iron, zinc, titanium, and magnesium. The heterogeneous metal element may be solidified to a range of 4 wt% or less, and the heterogeneous metal element may be solidified in an aluminum-based matrix in a substitutional or interstitial manner, but the present disclosure is not limited thereto. According to an embodiment, considering the atomic size and crystal structure of aluminum, the heterogeneous metal element, and a non-metallic heterogeneous element, the heterogeneous metal element may be mainly solidified in a substitutional manner and the heterogeneous non-metallic element may be mainly solidified in an interstitial manner.

[0023] An aluminum alloy as a solid solution according to an embodiment of the present disclosure may be fabricated using a casting process. According to an embodiment, the fabrication of the aluminum alloy may be initiated by providing melt. For example, the melt may be provided by heating pure aluminum by using an electric melting furnace.

[0024] In order to provide a non-metallic element that is solidified in the aluminum-based matrix, oxide particles or nitride particles of the heterogeneous metal element may be added to the melt. The oxide particles or nitride particles may have an average size (or diameter) from about 20 nm to about 100 nm. When the average size of the particles exceeds 100 nm, the oxide particles or nitride particles of the heterogeneous metal element may not be decomposed or may not be dispersed evenly in the aluminum matrix, and thus it becomes easier to form the second phase and it becomes difficult to form a solid solution of a non-metallic element. When the average size of the particles is less than 20 nm, it becomes difficult for the particles to be uniformly dispersed in the aluminum matrix due to the attractive force between the particles, and thus the second phase may be formed or solidification may become difficult.

[0025] The heterogeneous metal element may be copper, iron, zinc, titanium, magnesium or a mixture of two or more thereof, and the oxide particles or nitride particles may be, for example, copper oxide powder, iron oxide powder, zinc oxide powder, titanium oxide powder, magnesium oxide powder, copper nitrate powder, iron nitride powder, zinc nitride powder, titanium nitride powder, magnesium nitride powder, or a mixture of two or more thereof. The powder selected from among the above-stated powders may be added to the melt within a range of 1 wt% or less of aluminum, which is the solidifying rate of the non-metallic element. A stirring process for uniform mixing of the powder added into the melt may be performed.

[0026] The melt may be maintained at a temperature at which the added oxide particles or nitride particles may be decomposed. For example, while maintaining the melt at a temperature in the range of 500°C to 1,000°C, the melt may be stirred with the added particles, such that the added particles may be homogeneously decomposed. In this process, the particles are decomposed into the heterogeneous metal element and the non-metallic element and are uniformly dispersed in the melt, and thus the heterogeneous metal element and the non-metallic element may be solidified in the aluminum-based matrix. According to an embodiment, at this stage, the heterogeneous metal element and the non-metallic element may be completely solidified. Alternatively, according to another embodiment, the non-metallic element may be completely solidified in a subsequent additional heat treatment process.

[0027] The heterogeneous metal element and the heterogeneous non-metallic element are uniformly dispersed in the melt and then cooled to form an aluminum casted material. According to another embodiment, an operation for artificially aging a casted material at a high temperature may be further performed to form the aluminum casted material. The artificial aging treatment may increase the strength of an aluminum alloy.

[0028] According to another embodiment, the aluminum casted material may be subjected to a plastic deformation process to form a processed aluminum material. The plastic deformation process may be a cold process and, through the plastic deformation process, work hardening of the aluminum casted material may occur. The plastic deformation

process may be performed by rolling or pressing the aluminum casted material. However, the processes are merely examples, and the present disclosure is not limited thereto. Any process capable of providing appropriate compression or shearing stress that causes deformation may be performed. A twin boundary or partial dislocation described below may be induced through the plastic deformation process.

[0029] According to another embodiment, a heat treatment may be performed on the aluminum casted material or on the processed aluminum material. The heat treatment may be carried out at temperatures within different ranges according to purposes. In unlimited examples, a heat treatment for solidification may be performed at a temperature from about 400°C to about 500°C, a heat treatment for artificial aging may be performed at a temperature from about 120°C to about 180°C for a period of time from about 6 hours to about 24 hours. A heat-treated aluminum material may maintain all of the microstructure, the strength, and the elongation as described above even after the heat treatment(s).

[0030] The inventors of the present disclosure conducted structural analysis and evaluation of elongation performance for an aluminum casted material, a processed aluminum material, or a heat-treated aluminum material fabricated as described above. As a result, the presence of twin boundaries and partial dislocations were confirmed in all of the aluminum casted material, processed aluminum material, and heat-treated aluminum material, and remarkable characteristics including significant decrease of the stacking fault energy of an aluminum alloy due to the solidification of oxygen or nitrogen and the improved elongation ratio due to the same were obtained.

[0031] FIGS. 1A and 1B are transmission electron microscope (TEM) analysis images showing the microstructure of an aluminum alloy according to an embodiment of the present disclosure.

[0032] Referring to FIGS. 1A and 1B, the aluminum alloy may be an aluminum casted material in which zinc is incorporated as a metallic heterogeneous solute and oxygen is incorporated as a non-metallic solute to form the aluminum casted material as a solid solution. In an example, zinc and oxygen may be incorporated in the aluminum-based matrix to an amount of about 0.5 wt% each, which is less than or equal to 1 wt% of the aluminum. In an example, to incorporate the oxygen as a solute for the solid solution of aluminum alloy, zinc oxide powder may be added to a molten aluminum, and then the zinc powder may be decomposed and homogeneously mixed in the molten aluminum.

[0033] It is showed that the aluminum alloy has a twin boundary (indicated by a yellow arrow in FIG. 1A) whose lattices on both sides are symmetrical to each other, or a partial dislocation (indicated by a yellow arrow in FIG. 1B). The twin boundary is a structure in which atoms on a first side and atoms on a second side are symmetrically arranged with an interface as a mirror between the both sides as if the atoms. The twin boundary may be formed through a mechanical plastic deformation or an aging treatment after plastic deformation.

[0034] While an elongation ratio of the aluminum alloy is improved as the stacking fault energy (SFE) is reduced due to the incorporation of oxygen as the solute, the twin boundary effectively hinders slip action of atomic plane for propagating a dislocation, thereby providing a mechanism for enhancing material strength of the aluminum alloy. Therefore, the aluminum alloy according to the embodiment of the present disclosure exhibits improved workability due to improved elongation ratio and simultaneously improved mechanical strength.

[0035] FIG. 2 is a graph showing a result of X-ray diffraction (XRD) analysis for measuring stacking fault energy of an aluminum alloy having a twin boundary or partial dislocation according to an embodiment of the present disclosure. As a method of calculating stacking fault energy, a method of calculating the stacking fault energy based on an X-ray diffraction analysis result was utilized to obtain the stacking fault energy of the aluminum alloy according to the embodiment of the present disclosure.

[0036] Referring to FIG. 2, micro-deformation of about 5% of an as-cast casted aluminum alloy may be induced and then stacking fault energy may be calculated from shift and/or size changes of the XRD peaks. The respective constants required in the Equations 1 through 4 below may be calculated based on the disclosures and experimental results of the thesis, "The effect of nitrogen on the stacking fault energy in Fe-15Mn-2Cr-0.6C-xN twin boundary-induced plasticity steels" (Lee, et al., Vol. 92, pages 23-24 of Scripta Materialia, 2014), the thesis "Thermodynamic and physical properties of FeAl and Fe₃Al: atomistic study by EAM simulation" (Ouyang et al., the 2012 edition of Physica B. Vol. 407, pp. 4530-4536), and the thesis "The Relationship between Stacking-fault energy and x-ray measurements of stacking-fault probability and microstrain ((R.P. Reed and R.E. Schramm, the 1974 edition of J. Appl. Phys. Volume 45, page 4705).

[Equation 1]

$$\Delta(2\theta_{200} - 2\theta_{111}) = -\frac{90\sqrt{3}}{\pi^2} \left(\frac{\tan\theta_{200}}{2} + \frac{\tan\theta_{111}}{4} \right) P_{sf}$$

[0037] Here, θ_{200} is a Bragg angle of an aluminum crystal plane (200), θ_{111} is a Bragg angle of an aluminum crystal plane 111, and P_{sf} is a stacking fault probability. The θ_{200} may be determined according to Equation 2, and the θ_{111} may be determined according to Equation 3.

[Equation 2]

$$2\theta_{200} = 2\theta_{200}^{CW} - 2\theta_{200}^{ANN}$$

[0038] Here, θ_{200}^{CW} may be a Bragg angle of a crystal plane 200 of a sample in which the 5% deformation is induced, and $2\theta_{200}^{ANN}$ is a Bragg angle of a crystal plane 200 of an annealed sample. $2\theta_{200}$ may be a shift value of a relative X-ray peak observed on the crystal plane (200).

[Equation 3]

$$2\theta_{111} = 2\theta_{111}^{CW} - 2\theta_{111}^{ANN}$$

[0039] Here, θ_{111}^{CW} may be a Bragg angle of the crystal plane (111) of the sample in which the 5% strain is induced, and $2\theta_{111}^{ANN}$ may be the Bragg angle of the crystal plane (111) of the annealed sample. $2\theta_{111}$ may be a shift value of a relative x-ray peak appearing on the crystal plane (111).

[Equation 4]

$$SFE = \frac{K_{111} w_0 G_{(111)} a_0 A^{-0.37} \langle \varepsilon_{50}^2 \rangle_{111}}{\pi \sqrt{3} \alpha}$$

[Equation 5]

$$\alpha = \frac{C_{44} + C_{11} - C_{12}}{3P_{sf}}$$

[0040] In Equation 4, the value of K_{111w_0} may be 5.4 (refer to the thesis "Thermodynamic and physical properties of FeAl and Fe₃Al: atomistic study by EAM simulation"), $G_{(111)}$ is a shearing stress and may be about 24.3667 GPa for aluminum, a_0 may be a lattice constant and may be about 0.40495 nm, and A may be the vector constant and may be 2.8571 for aluminum. ε_{50}^2 is a micro-strain and the value thereof is determined according to intensity regarding a corresponding surface in an X-ray diffraction analysis. C_{44} , C_{11} , and C_{12} in Equation 5 are the elastic constants of materials, where the subscripted numbers indicate respectively given stress directions.

[0041] The stacking fault energy of pure aluminum may be about 162 mJ/m². However, in the case of the aluminum alloy according to the embodiment of the present disclosure, the stacking fault energy may be reduced by about 1/3. The stacking fault energy may be appropriately adjusted within a range of less than 100 mJ/m² depending on types or added amounts of the heterogeneous metal solute and heterogeneous non-metallic solute. Specifically, in the aluminum alloy according to an embodiment of the present disclosure, at least one type of defect from twin boundary and partial dislocation may appear. The stacking fault energy may be appropriately adjusted within a range of 100 mJ/m² even in the case of a processed material and a heat-treated material of an aluminum alloy according to an embodiment to the present disclosure in which oxygen or nitrogen is limitedly incorporated as a solute as well as the above-stated casted material.

[0042] Table 1 shows values of the stacking fault energies for various aluminum alloys, which are a casted material, a processed material, and a heat-treated material, according to an embodiment of the present disclosure, compared to the stacking fault energy of pure aluminum. In the A16061 alloy and the A356 alloy as well as pure aluminum, according to embodiments of the present disclosure, the stacking fault energies are remarkably reduced. The A16061 alloy and the A356 alloy are merely examples, and the present disclosure is not limited thereto. For example, elongation of other aluminum alloys from ALxxx series to AL7xxx series, such as AL1050, AL1060, AL1070, AL2011, AL2024, AL3003, AL4032, AL5052, AL5052, AL6063, or AL7075, may be improved through solidification of oxygen or nitrogen.

[Table 1]

Material	Composition	Stacking fault energy (mJ/m ²)
pure aluminum	100 % AL	162
cast aluminum material	100 % AL-O	48.65
processed aluminum material	AL6061-O	60.55
heat-treated aluminum Material	AL6061-O	82.4

[0043] The reduction of the stacking fault energy may facilitate formations of the twin boundary and the partial dislocation, and thus elongation ratio of the aluminum alloy may be improved while securing strength thereof.

[0044] FIGS. 3A through 3C are stress-deformation graphs showing results of measurement of elongation ratios of aluminum alloys having different compositions according to an embodiment of the present disclosure.

[0045] Referring to FIG. 3A, an elongation ratio of an oxygen-solidified aluminum alloy (see the curve As-cast A356-O), which is a casted material according to an embodiment of the present disclosure, increases by up to 100% as compared to a casted material (see the curve As-cast A356) according to a comparative embodiment. The increase of the elongation ratio may be attributed to the reduction of stacking fault energy according to an embodiment of the present disclosure.

[0046] Referring to FIG. 3B, the elongation ratio of an oxygen incorporating aluminum alloy as a solid solution (see the curve Treated A356-O), which is a heat-treated material according to an embodiment of the present disclosure, increases by up to 100% as compared to a heat-treated aluminum alloy (see the curve Treated A356) according to a comparative embodiment. Furthermore, the tensile strength (M) of the oxygen-incorporating aluminum alloy according to an embodiment of the present disclosure is improved by 30% or more as compared to the heat-treated aluminum alloy according to a comparative embodiment, together with the improvement of the elongation ratio. The improvement in the tensile strength is due to the reduction of stacking fault energy and a twin boundary and/or a partial dislocation associated with the same.

[0047] Referring to FIG. 3C, an A356 alloy (see the Curved Treated A356-O), which is another processed material according to an embodiment of the present disclosure with oxygen incorporated in the material, has an enhanced tensile strength thereof by 30% and the elongation ratio thereof was also increased by 100% or more.

[0048] The reduced stacking fault energy may improve the elongation of an aluminum alloy, thereby improving the workability of the aluminum alloy. The aluminum alloy is not limited to a casted material, and the elongation ratio may be improved in both of the processed material and the heat-treated material as described above.

[0049] According to another embodiment of the present disclosure, the aluminum alloy may have a structure in which a precipitated compound is dispersed in an aluminum alloy matrix. The precipitation compound refers to a chemical compound which is able to be formed by incorporating aluminum, a transition metal or a non-metallic element. The aluminum-based matrix refers to a matrix formed of pure aluminum or a conventional aluminum alloy. The aluminum alloy may be fabricated via a casting process described below.

[0050] FIG. 4 is a flowchart of a method of fabricating an aluminum alloy according to an embodiment of the present disclosure.

[0051] Referring to FIG. 4, according to an embodiment of the present disclosure, melt of an aluminum alloy may be provided (operation S10). The melt may be provided by heating the aluminum alloy, for example, by using an electric melting furnace. The heating temperature of the melt may be within a range from 650 to 850 . The heating temperature of the melt is merely an example, and an appropriate temperature may be implemented according to compositions of the aluminum alloy in the melt and/or an impurity in the aluminum alloy. Therefore, the present disclosure is not limited thereto.

[0052] The aluminum alloy may include any alloying element that may be a solute to form a solid solution of aluminum. According to an embodiment, the alloying element may include a transition metal. For example, the transition metal may be scandium (Sc), yttrium (Y), titanium (Ti), zirconium (Zr), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), silver (Ag), zinc (Zn), or at least two or more thereof. According to an embodiment, the transition metal may include at least one of chromium (Cr), iron (Fe), and manganese (Mn), which belong to Groups VI to VIII element in the period 4. According to another embodiment, in addition to the transition metal, the alloying element may further include a non-transition metal element, such as silicon (Si), magnesium (Mg), tungsten (W), calcium (Ca), strontium (Sr), and beryllium (Be). Furthermore, the aluminum alloy may be a known alloy including the transition metal. For example, as the known alloy, an A356 alloy including Fe from 0.2 to 0.3 wt% or an A6061 alloy including Fe from 0.5 to 0.7 wt% is available.

[0053] Herein, a transition metal actually included in an aluminum alloy as a starting material provided as a melt from among the above-stated transition metals may be referred to as a first transition metal, whereas a transition metal not

included in the aluminum alloy as the starting material and is of a kind different from the first transition metal may be referred to as a second transition metal. For example, when chromium (Cr), iron (Fe), and manganese (Mn), which are transition metals, are included as the alloying element in the molten aluminum as the starting material, chromium (Cr), iron (Fe) and manganese (Mn) that are already included in the molten aluminum may be referred to as the first transition metals in the present specification. According to an embodiment, powder of a compound between at least one of the first transition metals and a non-metallic element may be added into the molten aluminum including already the first transition metals to form a casted material therefrom and then heat treatment is performed thereto, thereby forming a ternary precipitation compound including at least one of the first transition metals in an aluminum-based matrix. According to another embodiment, since the first transition metal is preliminarily included in the molten aluminum, powder of a compound of a non-transition metal and a non-metallic element is added to the molten aluminum to form a casted material and heat treatment is performed thereto, thereby forming a ternary precipitation compound including the aluminum, the first transition metal, and the non-metallic element in the aluminum-based matrix.

[0054] According to another embodiment, when the molten aluminum includes only chromium (Cr) and iron (Fe) and does not include manganese (Mn), the first transition metal may include chromium (Cr) and iron (Fe) and manganese (Mn) not included in the molten aluminum may be referred to as a second transition metal. As described below, powder of a compound between the second transition metal and a non-metallic element may be added to the molten aluminum to form a casted material and then heat treatment may be performed thereto, thereby forming a ternary precipitation compound including at least one of the first transition metal and the second transition metal in an aluminum-based matrix.

[0055] According to another embodiment, there is no transition metal in the molten aluminum. In this case, powder of a compound between the second transition metal and the non-metallic element may be added to the aluminum melt to form a casted material and then a heat treatment may be performed thereto, thereby forming a ternary precipitation compound including the second transition metal in an aluminum-based matrix.

[0056] A non-metallic element-containing precursor including at least one of oxygen (O), nitrogen (N), and carbon (C) may be added to and mixed in the molten aluminum (operation S20). Next, the added non-metallic element-containing precursor may be decomposed in the molten aluminum, and thus the non-metallic element may be supersaturated in the molten aluminum (S30). The non-metallic element-containing precursor may include a compound of a first reaction compound, which is a compound between the first transition metal and the non-metallic element, or a second reaction compound, which is a compound between the second transition metal (a transition metal different from the first transition metal) and the non-metallic element. According to another embodiment, the non-metallic element-containing precursor may also be a third reaction compound, which is a compound between a non-transition metal and the non-metallic element.

[0057] According to an embodiment, when zinc (Zn), which is a first transition metal, is present as an aluminum alloying element in the molten aluminum, the first reaction compound may be, for example, an oxide including a second transition metal, e.g., chromium (CrO_2), and a non-metallic element-containing precursor including the first reaction compound may be added to the molten aluminum. In another example, the non-metallic element-containing precursor may include a third reaction compound including a non-transition metal element (e.g., silicon), e.g., silicon oxide (SiO_2). When the first transition metal already exists in the molten aluminum, the third reaction compound may be used as the non-metallic element-containing precursor, thereby forming a ternary precipitation compound including aluminum, a first transition metal, and a non-metallic element in a casted aluminum-based matrix.

[0058] In the case where a transition metal such as zinc, titanium, copper, and iron is not included in the molten aluminum as the alloying element, the non-metallic element-containing precursor may be a second reaction compound that is a compound of a second transition metal and a non-metallic element, where a non-metallic element-containing precursor including zinc oxide (ZnO), titanium oxide (TiO_2), copper oxide (CuO_2), iron oxide (Fe_2O_3), copper nitride (CuN), iron nitride (FeN), zinc nitride (ZnN), titanium nitride (TiN), magnesium nitride (MgN), or a mixture thereof may be added to the molten aluminum. These are merely examples, and the present disclosure is not limited thereto.

[0059] According to another embodiment, the non-metallic element-containing precursor may include a third reaction compound between a non-transition metal element and a non-metallic element. For example, the third reaction compound may include a reaction compound between a non-transition metals, such as aluminum (Al), magnesium (Mg), silicon (Si), or tungsten (W), and the non-metal element, that is, aluminum oxide (Al_2O_3), aluminum nitride (AlN), magnesium oxide (MgO_2), silicon oxide (SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), tungsten oxide (WO), tungsten nitride (WN), or a mixture thereof. However, they are merely examples, and the present disclosure is not limited thereto. Furthermore, the first through third reaction compounds, which are the non-metallic element-containing precursors, may be added to the molten aluminum alone or in combination of two or more thereof.

[0060] According to an embodiment, the non-metallic element-containing precursor may be provided in the form of powders, such that the specific surface area of the non-metallic element-containing precursor may increase and the non-metallic element-containing precursor may be easily decomposed in the molten aluminum. For example, the non-metallic element-containing precursor may have an average diameter within a range from about 5 nm to about 50 nm. When the diameter is more than 50 nm, the decomposition of the non-metallic element-containing precursor becomes difficult, and thus formation of a precipitation compound described later may be difficult. The above-stated first reaction

compound and second reaction compound may be added to the molten aluminum alone or in combination with each other.

[0061] According to an embodiment, the non-metallic element-containing precursor may be mixed in the range from 0.01 wt% to 5.0 wt% of the total weight including the molten aluminum and the non-metallic element-containing precursor. When the mixing amount of the non-metallic element-containing precursor is less than 0.01 wt%, it is difficult for the non-metallic element to be supersaturated in the molten aluminum alloy. On the contrary, when the mixing amount exceeds 5.0 wt%, it is difficult to form a precipitation compound having a uniform composition including three components, that is, aluminum, a transition metal, and a non-metallic element. When an excessive amount of non-metallic element-containing precursor is present in the molten aluminum, formation of a second phase, such as a reaction compound between the transition metal and the non-metallic element or a reaction compound between the aluminum and the non-metal element, may be accelerated. The non-metallic element may be mixed over the solubility limit, such that the non-metallic element may be supersaturated with respect to aluminum of an aluminum-based matrix at the room temperature within the composition range of the non-metallic element-containing precursor.

[0062] The molten aluminum in which the non-metallic element is uniformly mixed and supersaturated is solidified, and thus a casted material is formed (operation S40). The molten aluminum may be solidified by cooling the same.

[0063] Next, the solidified casted material may be heat-treated to precipitate a ternary reaction compound between aluminum-a transition metal-a non-metallic element, thereby forming the precipitated compound uniformly dispersed in an aluminum-based matrix (operation S50). The transition metal of the ternary reaction compound may include at least one kind of transition metal. For example, the ternary reaction compound may be an aluminum-zinc-oxygen ternary reaction compound or the ternary reaction compound may include iron, chromium, scandium, manganese or two or more metals in place of or in addition to zinc. These compounds are merely examples, and the present disclosure is not limited thereto. The non-metallic element of the ternary reaction compound may also include at least one non-metallic element. For example, the ternary reaction compound may be aluminum-zinc-oxygen ternary reaction compound or may include nitrogen, carbon, which are non-metallic elements other than oxygen, or all of them in addition to or in place of oxygen.

[0064] As described below with reference to FIG. 4, the precipitation compound may be a nano-sized crystal grain and may have an average size from about 10 nm to about 1 μ m. When the size of the precipitated compound is less than 10 nm, it cannot strongly interact with dislocations formed in the aluminum alloy and cannot contribute to the improvement of strength. When the size exceeds 1 μ m, the precipitation compound becomes rather brittle, and thus it cannot contribute to the improvement of strength.

[0065] The precipitation compound, which is a ternary reaction compound, may be stably formed in the aluminum-based matrix through the heat treatment, rather than being formed in a cooling process for solidification as described later. As a result, according to an embodiment of the present disclosure, the precipitation compound may be uniformly formed in an aluminum-based matrix without segregation or coagulation as compared to a non-heated alloy.

[0066] The heat treatment may be performed at a temperature within a range from about 120 to about 600 . When the temperature is lower than 120 , precipitation of the reaction compound may not occur. When the temperature exceeds 600 , an aluminum-based matrix is melted and, even when the precipitation compound may be formed, the precipitation compound and the aluminum-based matrix are agglomerated with each other, and thus an aluminum alloy structure having the precipitation compound uniformly dispersed therein cannot be obtained.

[0067] According to an embodiment, the heat treatment may include a single heating operation or at least two heating operations. For example, a solidified intermediate product may be heat-treated at 540 for 12 hours and at 160 for 8 hours. The above-stated temperature ranges and times are merely examples and may be appropriately selected to prevent agglomeration and segregation of the precipitation compound.

[0068] According to an embodiment, the casted material may be further subjected to plastic working and hardening before the heat treatment (operation S45). The above plastic working may be performed through plastic deformation, such as rolling, extrusion, drawing, or forging. The plastic working may be a hot process or a cold process, but the present disclosure is not limited thereto. For example, the plastic working may be artificially aged without cold working after a solid solution treatment. The above-stated precipitation compound may be additionally formed in the aluminum-based matrix through the above-stated plastic working or the precipitation compound may have a strong interaction with a dislocation formed during the plastic deformation, and thus the strength of an aluminum alloy may be further improved.

[0069] The below examples relate to specific experimental examples. However, the examples are not intended to limit the invention, but are representative examples for illustrative purposes and, due to common electrical, chemical and physical characteristics of transition metals, embodiments other than those shown therein are also included in the present disclosure.

Experimental Example

[0070] An aluminum alloy (e.g., A356 alloy) including an aluminum alloy, iron as a first transition metal, and silicon as a non-transition metal was melted by using an electric heating furnace to form a melt. Next, particles or powder of zinc

oxide having an average particle size of about 30 nm, which is within a range from 5 nm to 50 nm, were added to the melt as a non-metallic element-containing precursor and decomposed. The zinc oxide particles were injected and stirred by about 1 wt% or 1.5 wt%, which is in the range from 0.01 wt% to 5.0 wt% of the total wt% of the melt. A non-metallic element was supersaturated in the melt of the aluminum alloy and solidified as it is to form a casted material of the aluminum alloy in which oxygen as a non-metallic element is supersaturated. Next, the casted material was subjected to a standard T6 heat treatment.

[0071] FIGS. 5A and 5B are transmission electron microscope images showing precipitation compounds in an aluminum-based matrix formed by heat treatment according to an embodiment of the present disclosure, and FIG. 5C is a graph showing compositions of the precipitation compounds analyzed via an energy dispersive X-ray spectroscopy (EDS). FIG. 6 is a scanning electron microscope image showing a cross-sectional microstructure of an aluminum alloy casted material supersaturated with a non-metallic element before heat treatment, according to a comparative embodiment.

[0072] The aluminum alloy shown in FIGS. 5A and 5B is an aluminum alloy in which a precipitation compound was formed after an aluminum alloy casted material to which a ZnO precursor is added by about 1.5 wt% was subjected to T6 heat treatment for 12 hours at 540 and for 8 hours at 160 . In order to observe the deformation behavior of the aluminum alloy including the precipitation compound, the aluminum alloy was subjected to tensile deformation of about 15%, and then observed with the transmission electron microscope. It can be observed that the precipitation compound (NP) according to an embodiment of the present disclosure strongly interacts with the dislocation (DL).

[0073] Referring to FIG. 5C, it may be observed that the precipitation compound includes three kinds of elements, aluminum-iron-oxygen. Here, silicon is a composition derived from an aluminum alloy existing in the melt and is independent from the composition of the precipitation compound. The precipitation compound is a new reaction compound between aluminum-transition metal-non-metallic element which are not precipitated from a conventional aluminum alloy, forms a very favorable interface with an aluminum-based matrix, and strongly interacts with a dislocation in the aluminum-based matrix, thereby improving strength of the aluminum alloy.

[0074] Referring to FIG. 6, the bright needle-shaped structure is a silicon phase in an aluminum alloy, and the dark region is an aluminum-based matrix. Since the aluminum casted material was not subjected to a heat treatment, no observable-sized precipitation compound according to an embodiment of the present disclosure is observed in the aluminum-based matrix.

[0075] FIG. 7 is a graph showing results of measuring tensile strength of an aluminum alloy according to an embodiment of the present disclosure and tensile strength of an aluminum alloy according to a comparative embodiment.

[0076] Referring to FIG. 7, an aluminum alloy according to an embodiment of the present disclosure is fabricated by adding a precursor powder of ZnO to the melt of an A356 alloy to form a casted material and performing a heat treatment to the casted material. The aluminum alloy according to the comparative embodiment was fabricated by forming a casted material without adding precursor powder to molten aluminum and performing heat treatment thereto under the same conditions. It may be seen that the tensile strength of the aluminum alloy according to the embodiment of the present disclosure (the solid line curve) is improved by about 35% or more as compared to the aluminum alloy according to the comparative embodiment (dotted line curve).

[0077] FIGS. 8A and 8B are graphs showing increases tensile strength and strength of aluminum alloys according to various compositions of a precipitation compound according to an embodiment of the present disclosure, respectively.

[0078] For example, referring to FIGS. 8A and 8B, various aluminum alloys including precipitation compounds containing transition metals, that is, manganese (curve b), titanium (curve c), and iron (b) formed in aluminum-based matrixes including originally 7 wt% of silicon and 0.3 wt% of magnesium all exhibit improved strengths as compared to an aluminum alloy including no transition metal (curve a). Particularly, the aluminum alloys including precipitation compound containing chromium and iron exhibits improved strength, and the aluminum alloy including precipitation compound containing manganese also exhibits improved tensile strength.

[0079] FIG. 9 is a graph showing results of measuring tensile strength of an aluminum alloy including a precipitation compound according to another embodiment and an aluminum alloy according to a comparative embodiment.

[0080] Referring to FIG. 9, the aluminum alloy according to an embodiment of the present disclosure is an aluminum alloy including a precipitation compound formed by adding 1.0 wt% of ZnO precursor powder to the melt of an aluminum alloy of Al-Si (7 wt%) -Mg (0.3 wt%)-Fe (0.3 wt%)-Sr (0.1 wt%). On the contrary, the aluminum alloy according to the comparative embodiment is an aluminum alloy obtained by forming a casted material without adding ZnO, which is a non-metallic element-containing precursor, to the melt of an aluminum alloy and heat-treating the casted material. It was observed that the aluminum alloy according to an embodiment of the present disclosure (solid line curve) shows an improvement in yield strength of about 22% as compared to the aluminum alloy according to the comparative embodiment (dotted curve).

[0081] FIG. 10 is a graph showing results of measuring tensile strength of an aluminum alloy (solid line curve) including a precipitation compound according to another embodiment and an aluminum alloy according to a comparative embodiment.

[0082] Referring to FIG. 10, the aluminum alloy according to an embodiment of the present disclosure indicated by the solid line is an aluminum alloy fabricated by forming a casted material by adding about 2.0 wt% of ZnO precursor powder to the melt of an aluminum alloy of Al-Si (2 wt%)-Mg (1.0 wt%)-Mn (0.3 wt%), re-crystallizing the casted material via 90 % plastic rolling, and performing a heat treatment thereto. The aluminum alloy according to the comparative embodiment is an aluminum alloy fabricated by forming a casted material without adding the precursor powder to the melt of an aluminum alloy, performing the plastic operation to the casted material, and heat-treating the same. The aluminum alloy according to an embodiment of the present disclosure exhibited yield strength improvement by about 13% as compared to the aluminum alloy according to the comparative embodiment.

[0083] As described above, an aluminum alloy including the precipitation compound between aluminum-transition metal-non-metallic element according to an embodiment of the present disclosure may be fabricated using a casting operation and a heat treatment operation. The above-described experimental examples are merely examples, and the present disclosure is not limited thereto. For example, even in the case of nitrogen and carbon, which are non-metallic elements capable of forming ternary reaction compounds as stable as a ternary reaction compound formed by using oxygen, which is a non-metallic element, may form a precipitation compound uniformly in an aluminum-based matrix, thereby improving strength of an aluminum alloy.

[0084] According to the above embodiments, material properties of an aluminum alloy are enhanced and improved by controlling stacking fault energy or employing a precipitation compound including a transition metal, which is obtained via a process employing nanoparticle precursor powder.

[0085] According to the embodiment of the present disclosure, there may be provided an aluminum alloy with high strength and improved workability based on elongation ratio improved as stacking fault energy is reduced due to solidification of a non-metallic element in an aluminum-based matrix and strength improved by a microstructure including a twin boundary or a partial dislocation.

[0086] According to another embodiment of the present disclosure, particles of a metal oxide or a metal nitride are added in the form of powders to the melt of aluminum or an aluminum alloy providing an aluminum matrix to reduce stacking fault energy and/or form a partial dislocation, thereby providing a highly-stretchable aluminum alloy having the above-described advantages in high production yield.

[0087] According to another embodiment of the present disclosure, a compound including aluminum-transition metal-non-metallic element or a compound including the above-stated elements is precipitated in an aluminum-based matrix via a heat treatment. As the precipitate is formed uniformly in the aluminum-based matrix and the precipitation compound strongly interacts with a dislocation, an aluminum alloy with significantly improved strength may be provided.

[0088] According to another embodiment of the present disclosure, a method of reliably fabricating an aluminum alloy having the above advantages may be provided.

[0089] It should be understood that embodiments described herein should be considered in a descriptive sense only and not for purposes of limitation. Descriptions of features or aspects within each embodiment should typically be considered as available for other similar features or aspects in other embodiments.

[0090] While one or more embodiments have been described with reference to the figures, it will be understood by those of ordinary skill in the art that various changes in form and details may be made therein without departing from the spirit and scope as defined by the following claims.

Claims

1. An aluminum alloy comprising:

an aluminum-based matrix; and
a precipitation compound dispersed in the aluminum-based matrix,
wherein the precipitation compound comprises a compound containing aluminum, one or more transition metals,
and one or more non-metallic elements.

2. The aluminum alloy of claim 1, wherein the average size of the precipitation compound is from about 10 nm to about 1 μ m.

3. The aluminum alloy of claim 1 or 2, wherein the transition metal comprises at least one of chromium (Cr), iron (Fe), and manganese (Mn).

4. The aluminum alloy of any one of the claim 1 to 3, wherein the non-metallic element is supersaturated in the aluminum alloy and comprises at least one of oxygen, nitrogen, and carbon.

5. The aluminum alloy of any one of the claims 1 to 4, wherein the precipitation compound is formed via a heat treatment.
6. The aluminum alloy of any one of the claims 1 to 5, wherein the aluminum-based matrix comprises aluminum alloy which comprises at least one of silicon (Si), zinc (Zn), magnesium (Mg), and copper (Cu).
7. A method of fabricating an aluminum alloy, the method comprising:
 - providing a melt of an aluminum alloy comprising aluminum and a first transition metal;
 - adding a non-metallic element-containing precursor comprising at least one of a first reaction compound between the first transition metal and a non-metallic element, a second reaction compound between a second transition metal different from the first transition metal and the non-metallic element, and a third reaction compound between a non-transition metal and the non-metallic element to the melt;
 - supersaturating the non-metallic element in the melt by decomposing the non-metallic element-containing precursor in the melt;
 - forming a casted material by solidifying the melt; and
 - forming a precipitation compound between aluminum, a transition metal, and a non-metallic element dispersed in an aluminum-based matrix by heat-treating the solidified casted material.
8. The method of claim 7, wherein the first transition metal comprises at least one of chromium (Cr), iron (Fe), and manganese (Mn).
9. The method of claim 7 or 8, wherein the non-metallic element comprises at least one of oxygen, nitrogen, and carbon.
10. The method of any one of the claims 7 to 9, wherein the non-transition metal of the third reaction compound comprises at least one of aluminum (Al), silicon (Si), magnesium (Mg), and tungsten (W).
11. The method of any one of the claims 7 to 10, wherein the non-metallic element-containing precursor is added to the melt in the form of powder having the average diameter within a range from about 5 nm to about 50 nm.
12. The method of any one of the claims 7 to 11, wherein the non-metallic element-containing precursor is added in the range from 0.01 wt% to 5.0 wt% of the total weight of the melt.
13. The method of any one of the claims 7 to 12, further comprising plastic working and hardening the solidified casted material before the hardened casted material is heat treated.
14. The method of any one of the claims 7 to 13, wherein the heat treatment is performed at a temperature within a range from 120 °C to 600 °C.

FIG. 1a

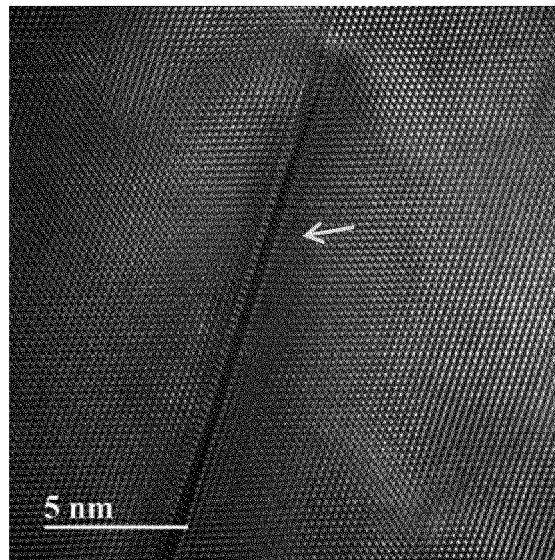


FIG. 1b

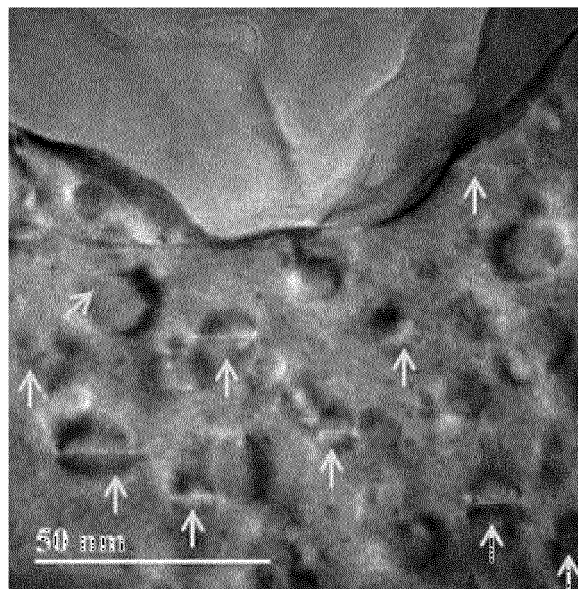


FIG. 2

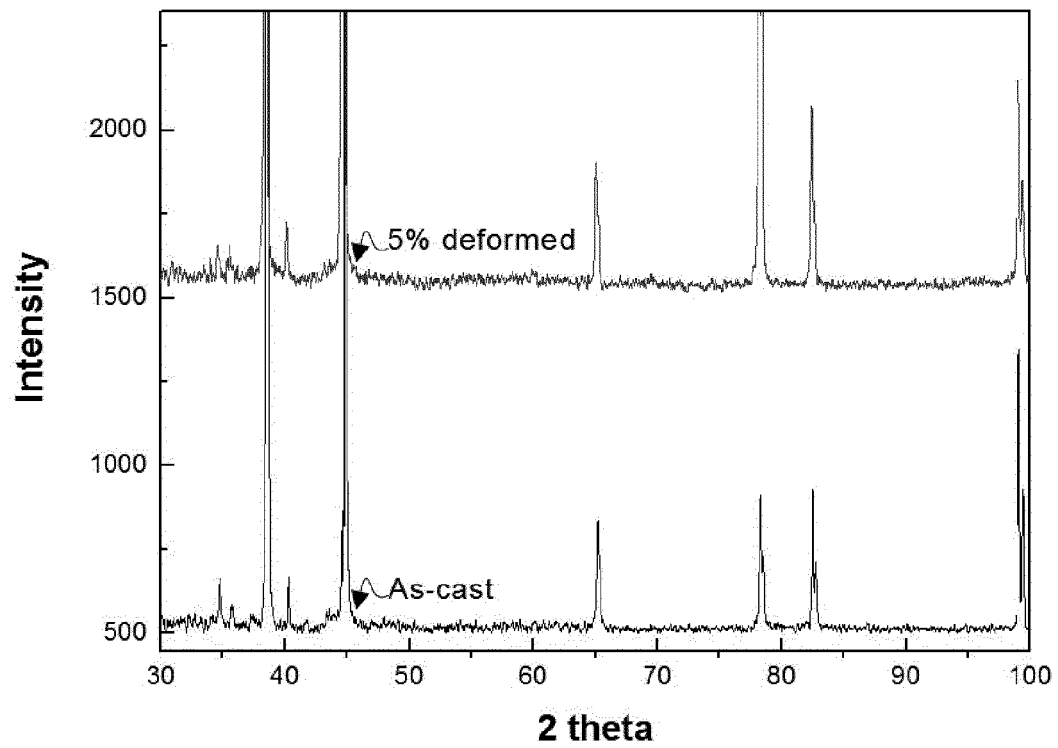


FIG. 3a

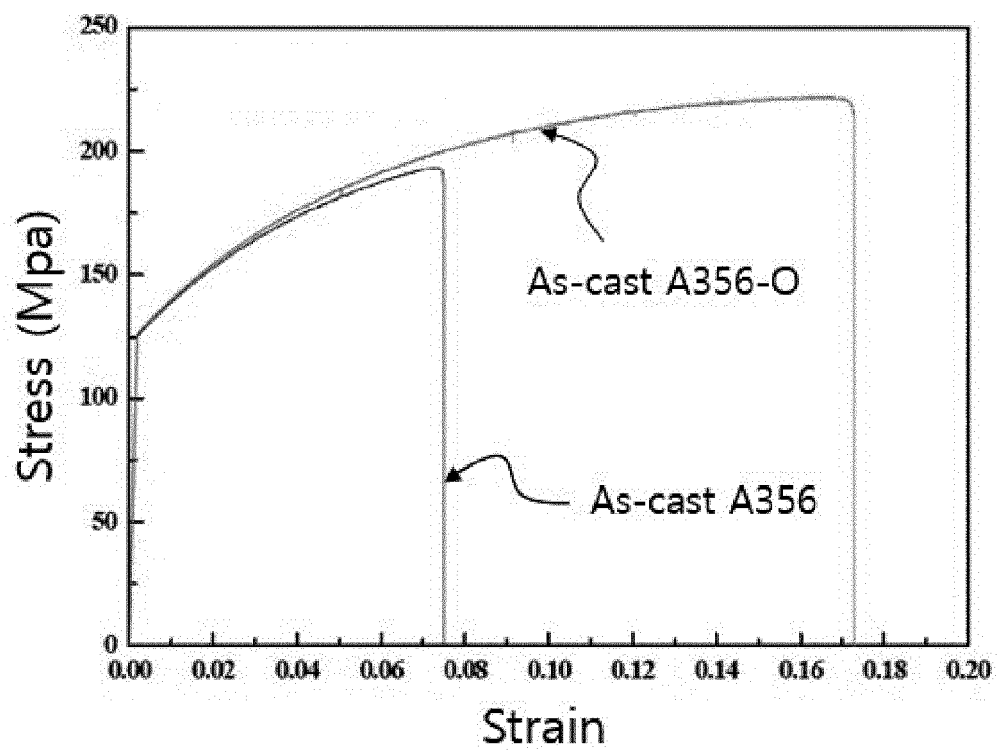


FIG. 3b

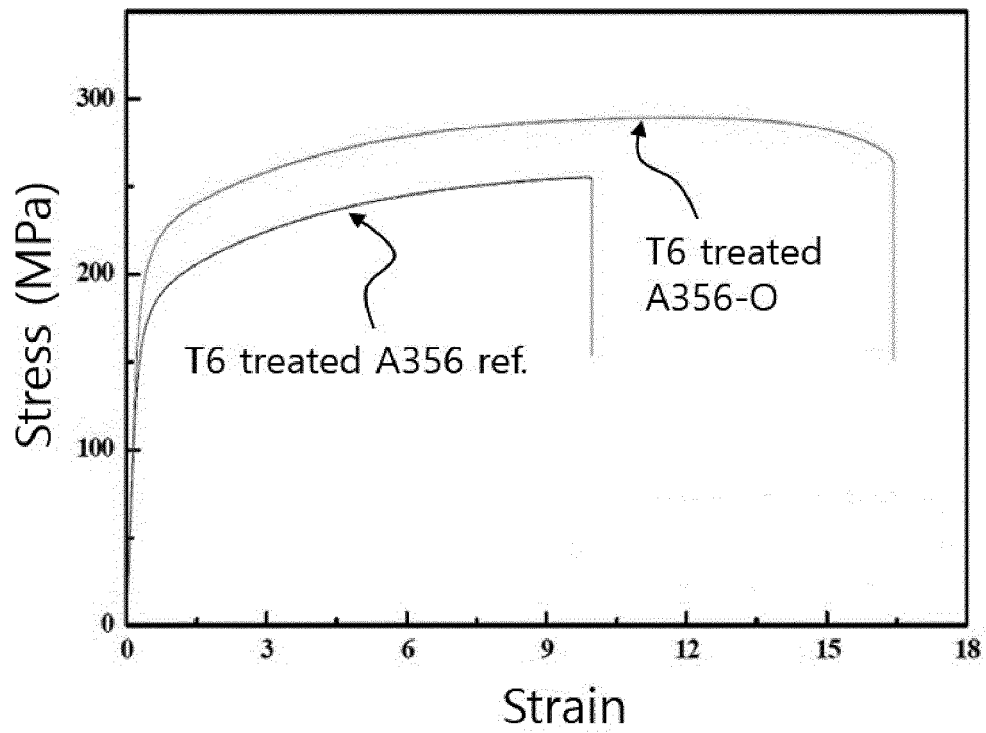


FIG. 3c

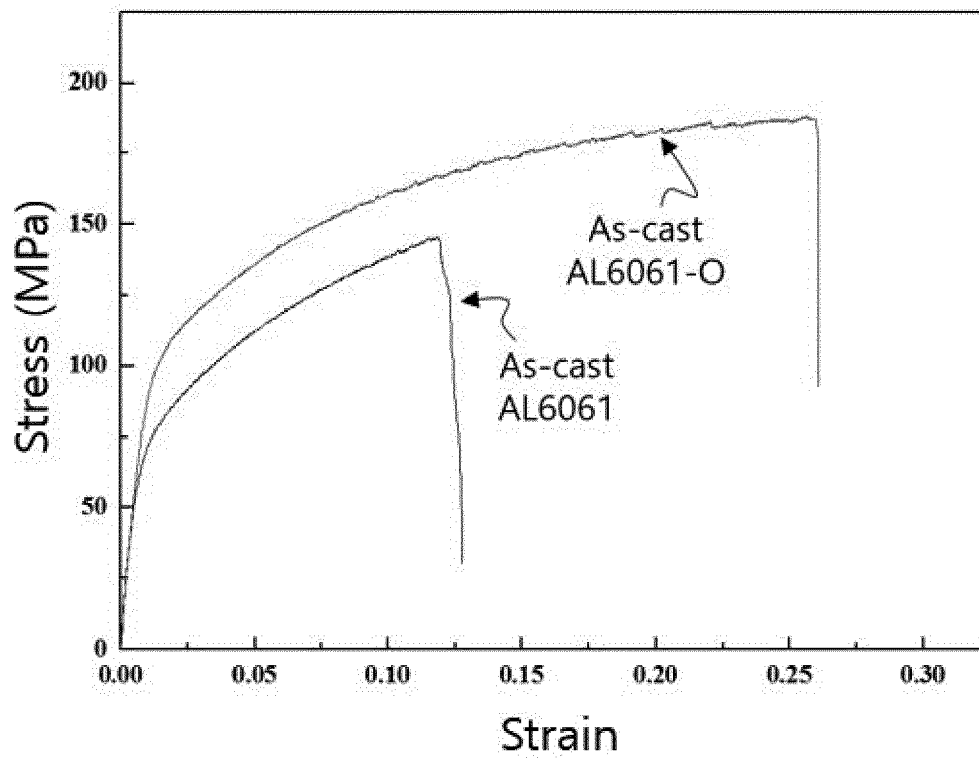


FIG. 4

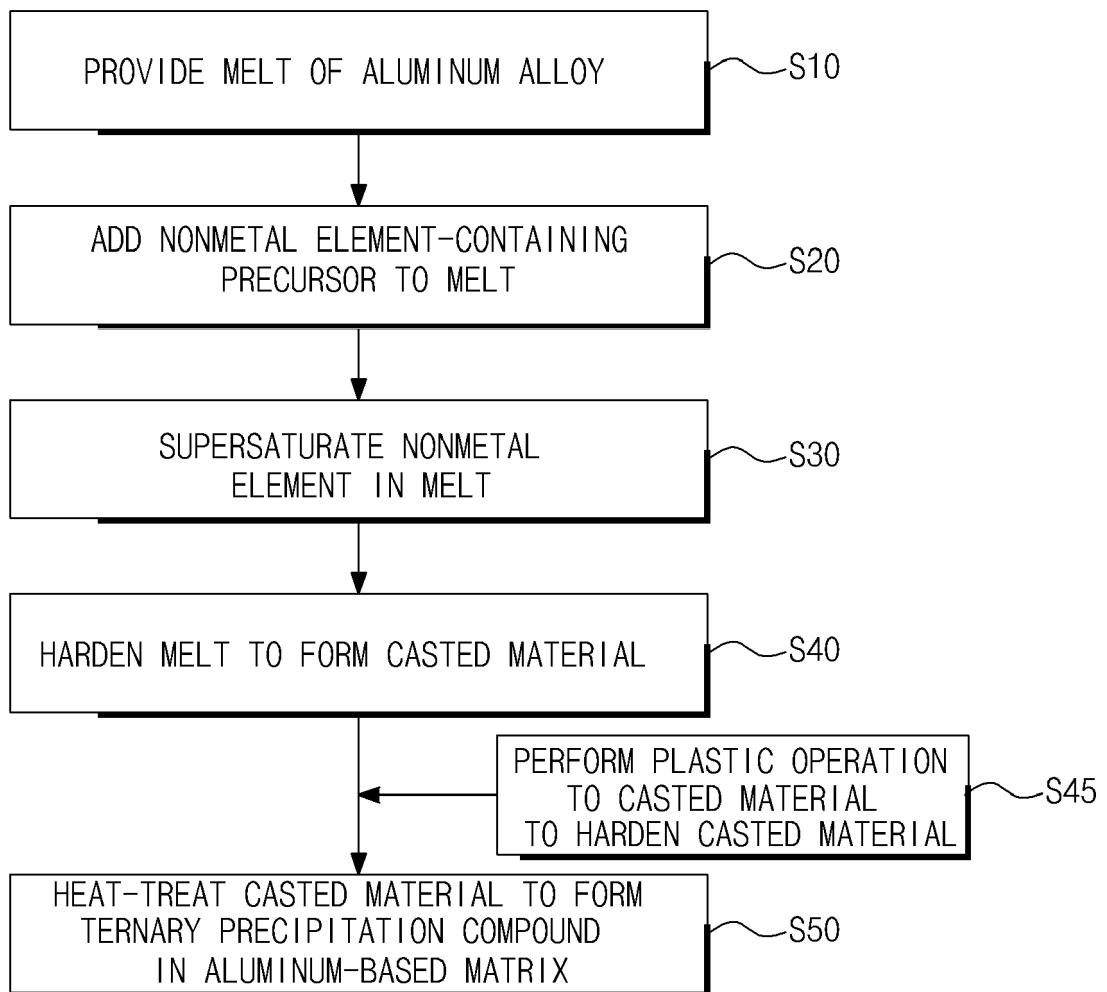


FIG. 5a

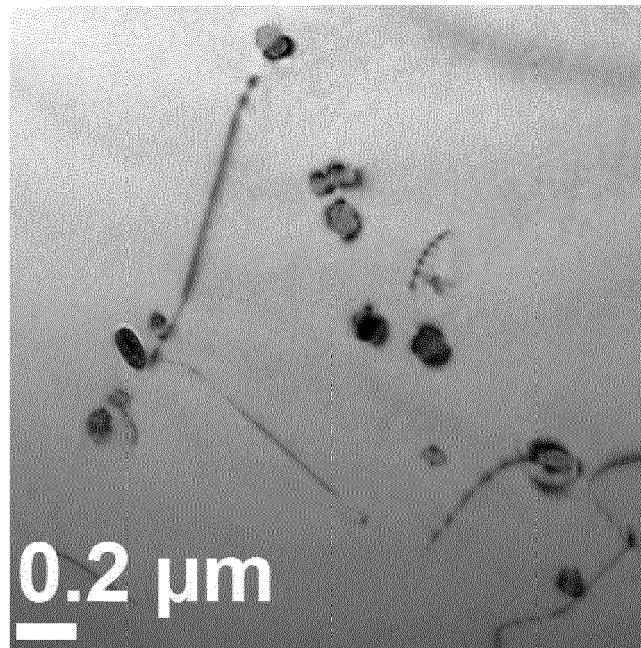


FIG. 5b

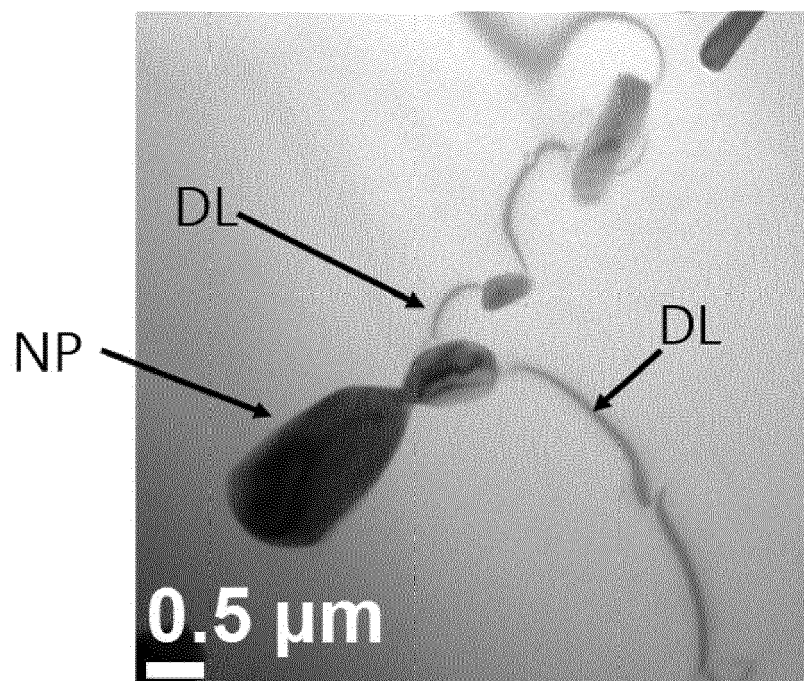


FIG. 5c

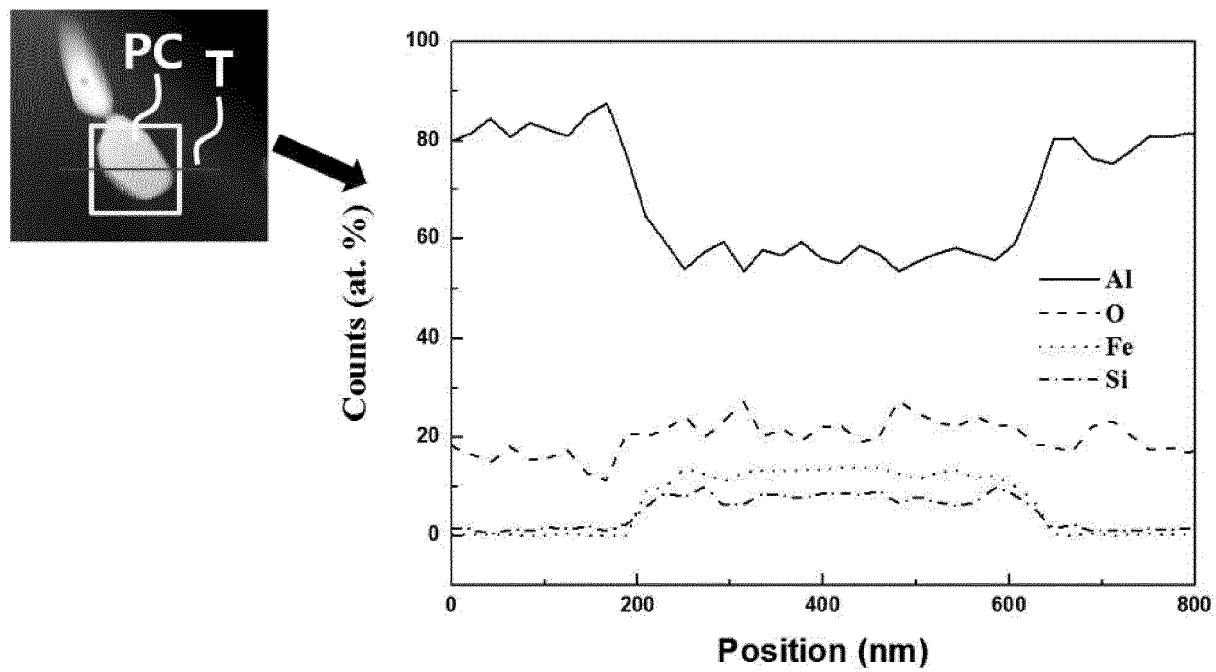


FIG. 6

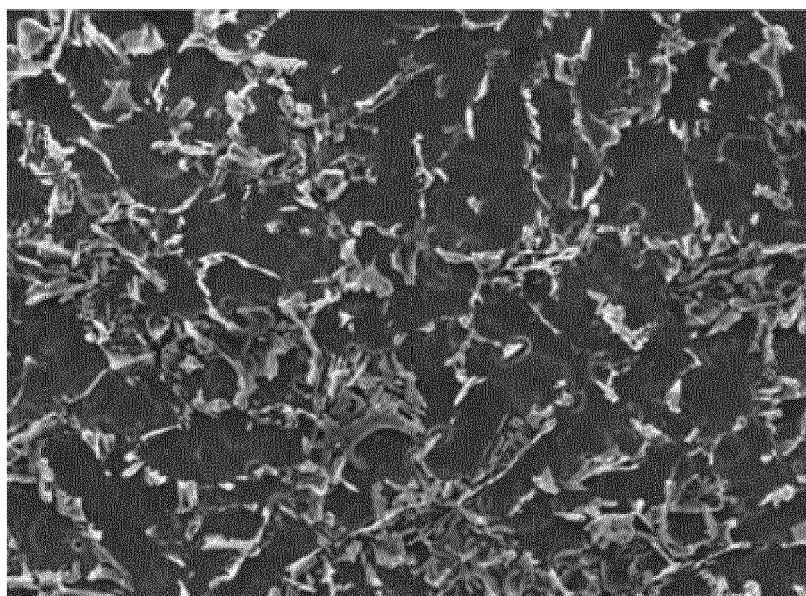


FIG. 7

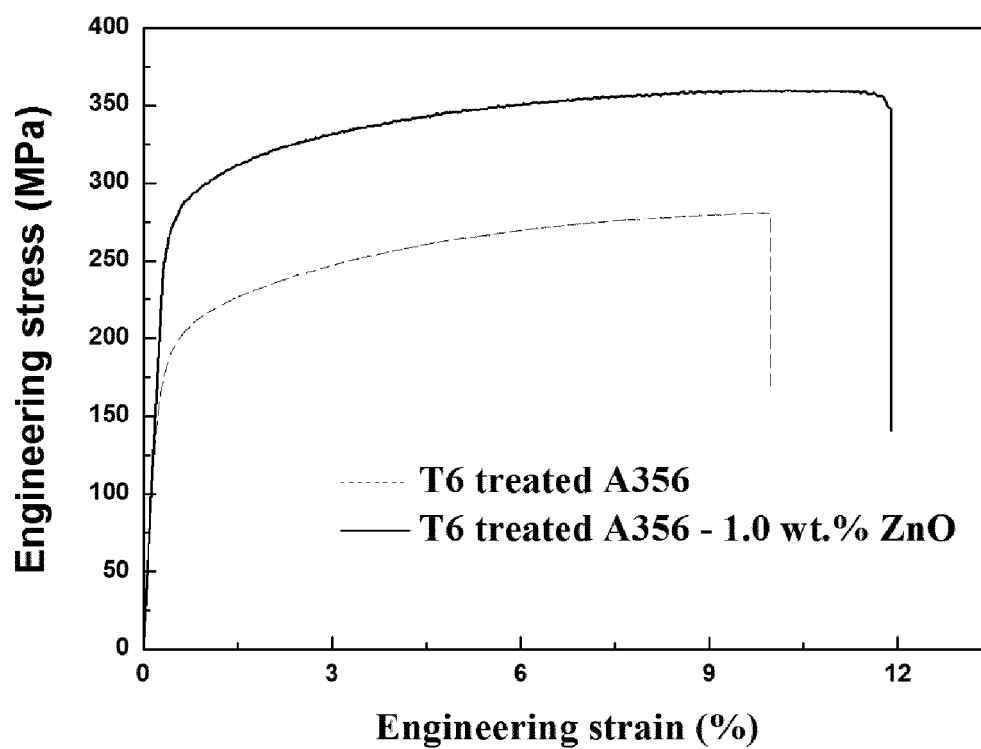


FIG. 8a

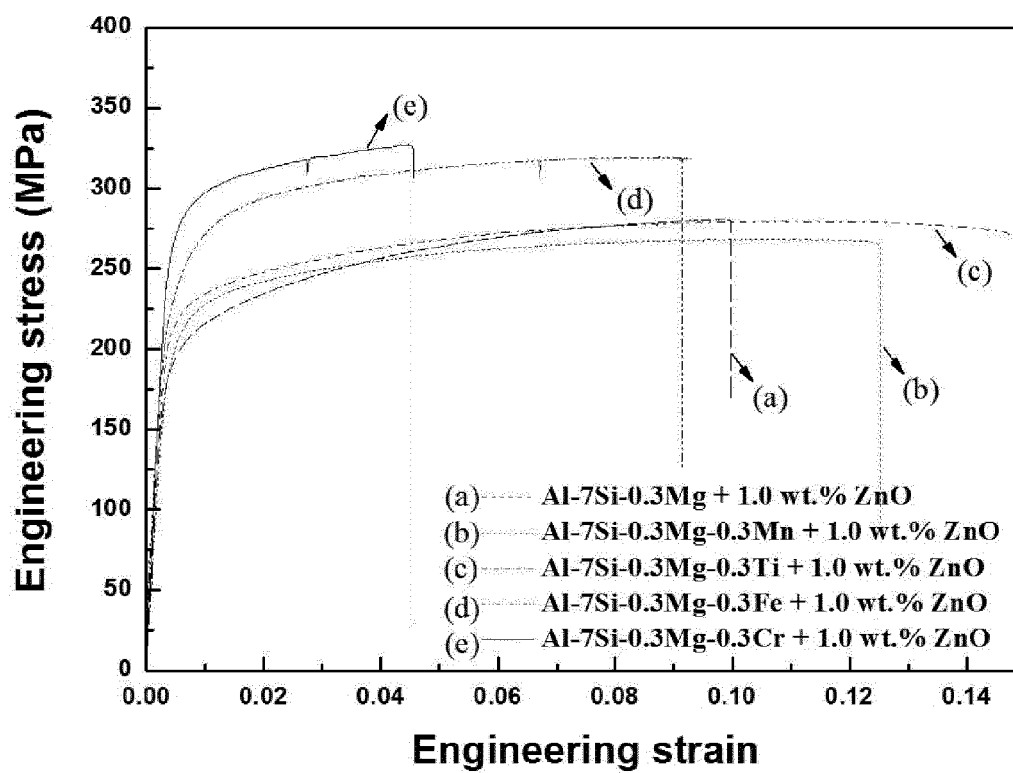


FIG. 8b

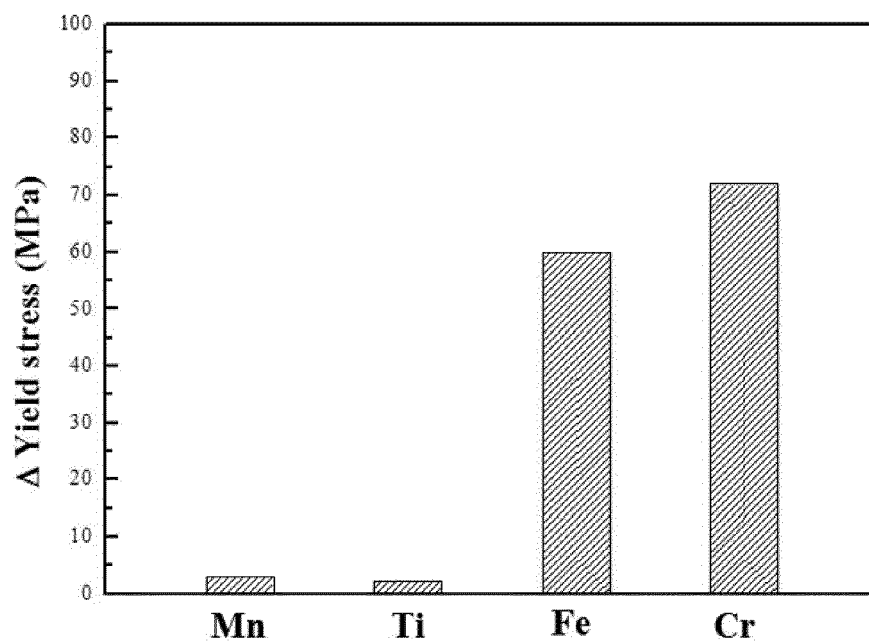


FIG. 9

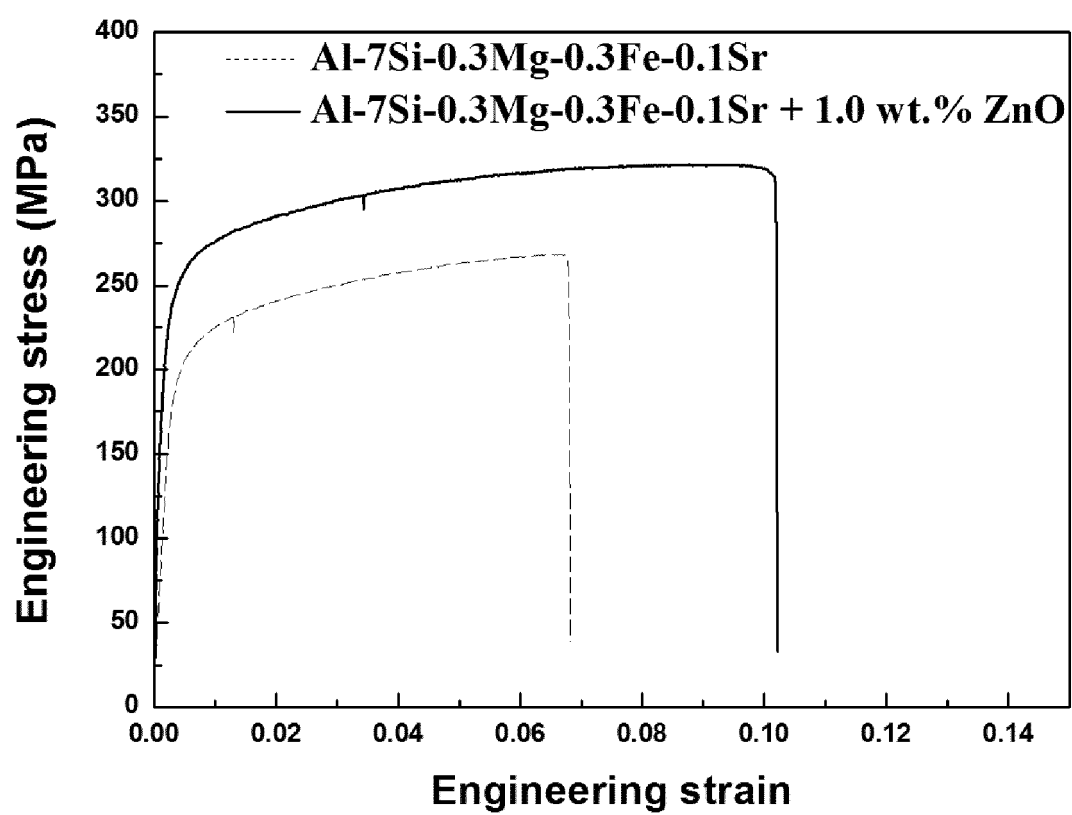
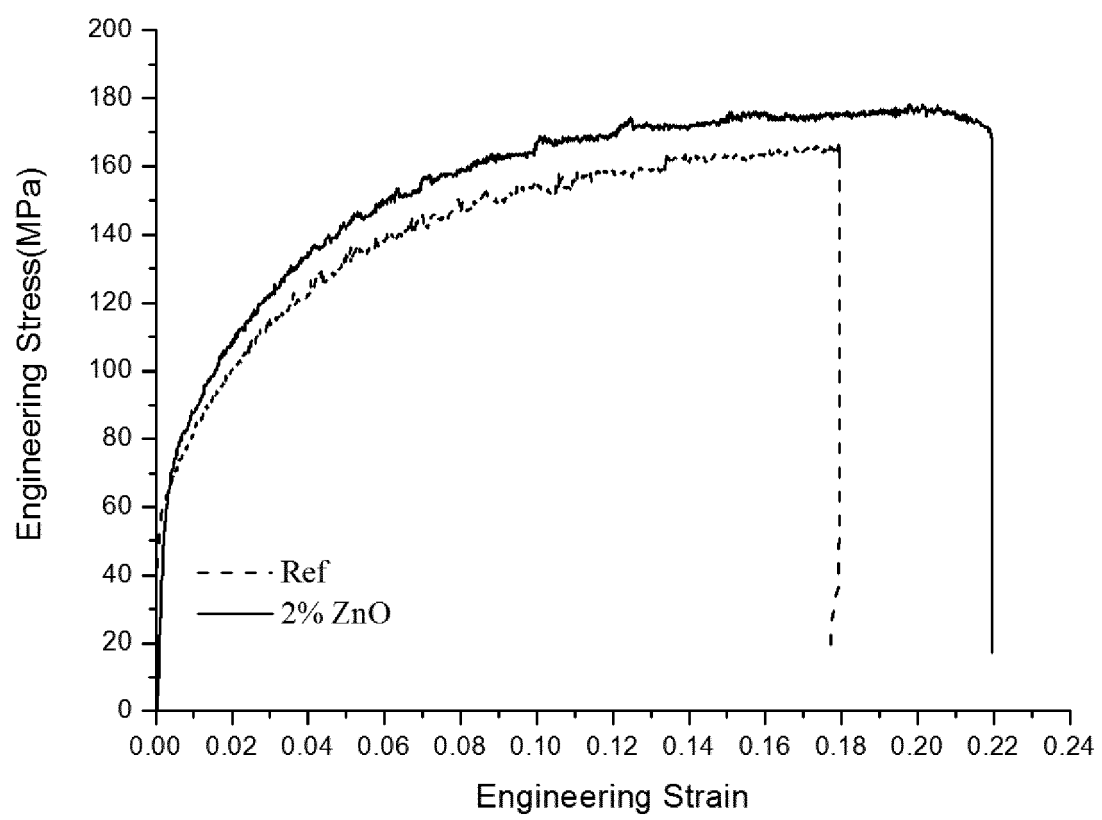


FIG. 10



REFERENCES CITED IN THE DESCRIPTION

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