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• **SAKURAYA Kazuyuki**

**Tsukuba-shi
Ibaraki 305-0047 (JP)**

• **KUSHIBE Atsumichi**

**Inzai-shi
Chiba 270-1352 (JP)**

• **INOUE Yasuhiko**

**Inzai-shi
Chiba 270-1352 (JP)**

• **UMEMURA Kenji**

**Nagoya
Aichi 460-0003 (JP)**

• **OTSUKA Hiroaki**

Tokyo 101-0052 (JP)

• **CHIBA Yuya**

Tokyo 101-0052 (JP)

• **SAKAI Hiromi**

Tokyo 101-0052 (JP)

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(71) Applicants:

- **National Institute for Materials Science
Tsukuba-shi, Ibaraki 305-0047 (JP)**
- **Takenaka Corporation
Osaka-shi, Osaka 541-0053 (JP)**

(72) Inventors:

- **SAWAGUCHI Takahiro
Tsukuba-shi
Ibaraki 305-0047 (JP)**
- **TAKAMORI Susumu
Tsukuba-shi
Ibaraki 305-0047 (JP)**
- **OHSAWA Yoshiaki
Tsukuba-shi
Ibaraki 305-0047 (JP)**

(74) Representative: **Emde, Eric**

**Wagner & Geyer Partnerschaft mbB
Patent- und Rechtsanwälte
Gewürzmühlstrasse 5
80538 München (DE)**

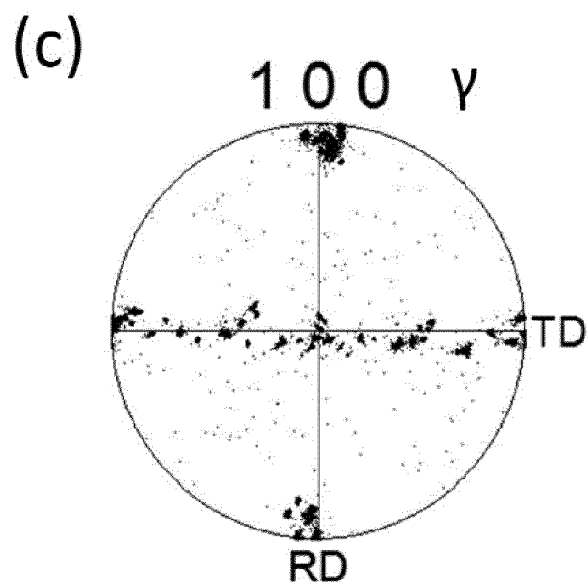
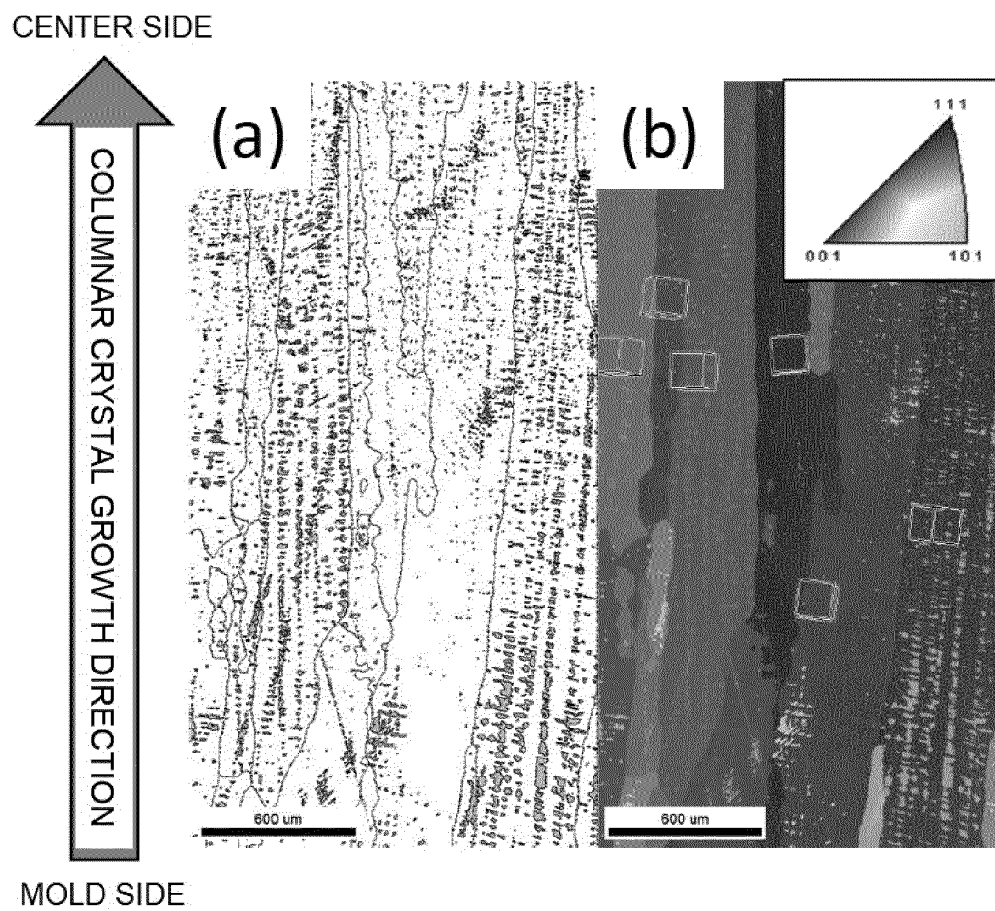
(54) **FE-MN-SI-BASED ALLOY CASTING MATERIAL HAVING EXCELLENT LOW-CYCLE FATIGUE PROPERTIES**

(57) The present invention provides a new Fe-Mn-Si-based cast alloy having excellent low-cycle fatigue properties that is useful as a structural building material or the like. An Fe-Mn-Si-based cast alloy according to one embodiment of the present invention contains Mn and Si as an essential component element, and one or more of Cr, Ni, Al, and C as an optional component element. The Fe-Mn-Si-based cast alloy has a component composition being $5 \text{ mass\%} \leq \text{Mn} \leq 35 \text{ mass\%}$, $1.5 \text{ mass\%} \leq \text{Si} \leq 6.5 \text{ mass\%}$, $0 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%}$,

$0 \text{ mass\%} \leq \text{Ni} \leq 15 \text{ mass\%}$, $0 \text{ mass\%} \leq \text{Al} \leq 3 \text{ mass\%}$, and $0 \text{ mass\%} \leq \text{C} \leq 0.4 \text{ mass\%}$, with the balance being Fe and inevitable impurities, and the component composition satisfies conditions of Formula (a): $37 < [\% \text{Mn}] + 0.3[\% \text{Si}] + 0.7[\% \text{Cr}] + 2.4[\% \text{Ni}] + 5.2[\% \text{Al}] + 28[\% \text{C}] < 45$, and Formula (b): $[\% \text{Ni}] + 30[\% \text{C}] + 0.5[\% \text{Mn}] > 0.75[\% \text{Cr}] + 1.125[\% \text{Si}] + 2[\% \text{Al}]$.

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Fig. 2



Description

Technical Field

5 **[0001]** The present invention relates to an Fe-Mn-Si-based cast alloy having excellent low-cycle fatigue life.

Background Art

10 **[0002]** Casting is an ancient metal processing method, and is capable of processing a metal into various shapes by heating the metal at a temperature higher than a melting point to be a liquid, and then, by pouring the liquid into a mold, cooling and solidifying the liquid into a desired shape. At the present time, casting is widely used for manufacturing small-lot products or mass-produced products such as various transport device parts or building frame parts of machine work. In addition, casting is used for manufacturing a solid material, a brittle material, and a product having a complicated shape which are difficult to be manufactured by plastic processing or cutting processing.

15 **[0003]** However, there is a case where a cast material has a cast defect such as a void, segregation, and an inclusion due to solidification shrinkage caused by a solid-liquid volume difference or redistribution of component elements. In general, such a cast defect noticeably decreases mechanical properties of the cast material, and thus, defect-free products have been conventionally produced by controlling solidification. Furthermore, important parts of some structural metal materials and the like are used after removing cast defects and homogenizing the material by performing a
20 homogenization heat treatment or plastic processing such as forging and rolling for promoting homogenization. Machine parts and the like which are used for a special use application requiring corrosion resistance or abrasion resistance generally have poor processing properties, and thus, these parts are usually prepared by casting, but there is also a case where such parts are used after homogenizing the material by performing a homogenization heat treatment after the casting.

25 **[0004]** However, even though various devices and improvements have been made in order to overcome the cast defect, in a case where large plastic strain is repeatedly loaded, as with low-cycle fatigue deformation, the cast defect becomes a generation source of a fatigue crack, and thus, a fatigue fracture easily occurs, and a low-cycle fatigue life of the cast material is noticeably shorter than that of a metal material subjected to a homogenization treatment.

30 **[0005]** For these reasons, when a cast material is used as a strength member, it is required that the safety ratio is set to a relatively high level compared to a material homogenized by forging, rolling, and the like, and that a stress which is generated in the cast material is set in an elastic range in order to prevent a fatigue fracture. Thus, it is uneconomical that a cast material is used as a strength member since it is not capable of utilizing the strength of a material sufficiently, for example, in a building member, the cast material can be used for only a member which is used in the elastic range even during a large earthquake.

35 **[0006]** In such a background, an Fe-Mn-Si-based alloy has recently been proposed as a core material of a seismic damper for a building in Patent Literature 1, and it is disclosed that the alloy exhibits an excellent low-cycle fatigue life. In addition, it is also disclosed that, in the Fe-Mn-Si-based alloy, martensitic transformation to an ε martensitic phase of a close-packed hexagonal (HCP) structure from a γ austenitic phase of a face-centered (FCC) structure due to plastic deformation in a certain direction, and subsequently, reverse martensitic transformation to the γ austenitic phase from
40 the ε martensitic phase due to plastic deformation in a reverse direction alternately reversibly occur. Thus, a change in atomic arrangement due to cyclic plastic deformation reversibly occurs, and the accumulation of a lattice defect that causes metal fatigue is not likely to occur, and therefore, the Fe-Mn-Si-based alloy exhibits an exponentially excellent low-cycle fatigue life, compared to a conventional material.

45 **[0007]** In Non Patent Literature 1, as a design guideline for improving the low-cycle fatigue life of the Fe-Mn-Si-based alloy, three conditions of (A) decreasing a free energy difference between a γ phase and an ε phase, (B) suppressing the formation of an α' martensitic phase of a body-centered structure, and (C) adding approximately 4 mass% of Si are disclosed. In addition, in Patent Literature 1, it is disclosed that, as a component design guideline for satisfying the condition of (A), an Mn equivalent weight ([%Mn]eq) is defined and described by the following Formula (X), and the blending ratio of the contents (mass%) of Mn, Cr, Ni, and Al ([%Mn], [%Cr], [%Ni], and [%Al]) as chemical components
50 satisfies the following Formula (Y).

$$[\%Mn]eq = [\%Mn] + [\%Cr] + 2[\%Ni] + 5[\%Al] \quad (X)$$

55

$$37 < [\%Mn]eq < 45 \quad (Y)$$

[0008] In addition, in Patent Literature 1, it is also disclosed that, as a component design guideline for satisfying the condition of (B), the blending ratio of the contents (mass%) of Mn, Cr, Ni, Si, and Al ([%Mn], [%Cr], [%Ni], [%Si], and [%Al]) satisfies the following Formula (Z), by incorporating the concept of a so-called Schaeffler phase diagram.

$$[\%Ni] + 0.5[\%Mn] > 0.75[\%Cr] + 1.125[\%Si] + 2[\%Al] \quad (Z)$$

[0009] Further, in Patent Literature 1, it is disclosed that a condition in which the Fe-Mn-Si-based alloy exhibits a significantly high low-cycle fatigue life compared to a general steel material is $0 \text{ mass\%} < \text{Si} < 6.5 \text{ mass\%}$, and is more desirably $2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%}$, on the basis of the optimal concentration of Si of 4 mass% in the condition of (C).

[0010] According to Non Patent Literature 2, on the basis of the design guidelines described above, an Fe-15Mn-10Cr-8Ni-4Si alloy having a low-cycle fatigue life that is 10 times as compared to a conventional material is developed. The alloy is applied as a shear panel type seismic damper of a skyscraper, and is expected as a high functional seismic damper having excellent durability against a long-period earthquake motion. Non Patent Literature 2 also discloses that such excellent fatigue durability is expected to be utilized not only in the shear panel type seismic damper, but also in various members.

[0011] However, in the Fe-Mn-Si-based alloy disclosed in Patent Literature 1, and Non Patent Literatures 1 and 2, an ingot is subjected to forging and rolling, and a heat treatment, so as to be molded into the shape of a plate and to make the coarse cast structure with preferential crystallographic orientation into a homogeneous and fine random equiaxial crystal structure, and thereby, a material with few defects is obtained, and in Patent Literature 1, and Non Patent Literatures 1 and 2, the low-cycle fatigue properties of the cast material are not disclosed or suggested.

[0012] As another Fe-Mn-Si-based alloy cast material, a fastener member of an Fe-Mn-Si-based shape-memory alloy is disclosed in Patent Literature 2. In Patent Literature 2, a method is provided in which a member having a shape close to that of a desired product member is prepared by casting, and then a heating treatment is appropriately performed, and thus, a fastener member is obtained by a simple manufacturing step without performing a hot processing step, and even a fastener member having a decorative or complicated shape that is not capable of being simply obtained in the conventional technique can be easily obtained. In addition, in Patent Literature 3, it is disclosed that, with regard to a joint for a pipe of an Fe-based shape-memory alloy produced by a centrifugal casting process, an area ratio of columnar crystals is set to be 50% or more in a macro-structure in a transverse plane, and thereby, a high inner diameter contraction rate is obtained.

[0013] In Patent Literatures 2 and 3, it is suggested that an Fe-Mn-Si-based shape-memory alloy joint manufactured by casting in a mold or continuous casting has sufficient deformation performance in order to exhibit a shape-memory effect; however, the durability against a low-cycle fatigue deformation is not disclosed or suggested.

[0014] Examples of a similar cast material that is widely used as a structural material include an abrasion-resistant cast steel having high Mn contents or a non-magnetic cast steel having high Mn contents. The abrasion-resistant cast steel having high Mn contents has excellent abrasion resistance and an excellent strength, and is used in a rail point or the like. The abrasion-resistant cast steel having high Mn contents has a high strength and a high processing hardening rate, and is difficult to be molded by plastic processing, and thus, is prepared by casting. In Patent Literature 4, it is also disclosed that an austenite phase in an abrasion-resistant cast steel having high Mn contents exhibits high durability against crack progression. In addition, in Patent Literature 5, a continuous casting method of a non-magnetic steel having high C and Mn contents is disclosed.

[0015] In Patent Literatures 4 and 5, it is described that mechanical properties of a cast steel having high Mn contents are excellent, and a mass production technology is sufficiently established, and it is also suggested that the fatigue durability of the cast steel is high; however, it is not disclosed or suggested whether a low-cycle fatigue life of 10 times as compared to a conventional material is obtained, which is obtained in regard to Fe-Mn-Si-based thick plate.

[0016] In Patent Literature 6, an austenitic cast metal containing 4.7 to 5.7 mass% of Si, 0.8 to 2.2 mass% of Cr, 2.0 to 5.5 mass% of Mn, 11 to 14 mass% of Ni, and 0.8 to 1.8 mass% of Cu is disclosed. However, the cast metal of Patent Literature 6 contains 2.1 to 3.1 mass% of C, and thus, is a material classified as cast iron and is completely different from the classification of cast steel in which C is contained less than 2.1 mass%. In addition, the fatigue durability is not mentioned in Patent Literature 6.

[0017] In Patent Literature 7, a non-magnetic cast material having high Mn contents, containing Si of 1.0 mass% or less, 10 to 20 mass% of Mn, 15.0 to 20.0 mass% of Cr, and 2.5 to 6.0 mass% of Ni, is disclosed. The cast material of Patent Literature 7 is classified as cast steel based on the content of C; however, the content of Si in the casting body is low, and the fatigue durability is not suggested in Patent Literature 7.

[0018] In Patent Literature 8, a high temperature abrasion resistant material containing 0.2 to 1.5 mass% of Si, 10 to 24 mass% of Mn, 12 to 20 mass% of Cr, and Ni of less than 4 mass% is disclosed. This high temperature abrasion resistant material is a material classified as cast steel since the content of C is 0.2 to 0.5 mass%, and it is mentioned in

Patent Literature 8 that abrasion resistance and crack resistance are excellent; however, the low-cycle fatigue life is not described in Patent Literature 8.

Citation List

Patent Literature

[0019]

Patent Literature 1: JP 2014-129567 A
 Patent Literature 2: JP 10-280061 A
 Patent Literature 3: JP 2001-082642 A
 Patent Literature 4: JP 2001-140039 A
 Patent Literature 5: JP 2013-173159 A
 Patent Literature 6: JP 2011-68921 A
 Patent Literature 7: JP 7-197196 A
 Patent Literature 8: JP 2014-1831360 A

Non Patent Literature

[0020]

Non Patent Literature 1: T. Sawaguchi, I. Nikulin, K. Ogawa, K. Sekido, S. Takamori, T. Maruyama, Y Chiba, A. Kushibe, Y Inoue, K. Tsuzaki, Designing Fe-Mn-Si alloys with improved low-cycle fatigue lives, Scripta Mater., 99 (2015) 49-52.
 Non Patent Literature 2: T. Sawaguchi, T. Maruyama, H. Otsuka, A. Kushibe, Y Inoue, K. Tsuzaki, Design Concept and Applications of Fe-Mn-Si-Based Alloys-from Shape Memory to Seismic Response Control, Mater. Trans., 57 (2016) 283-293.
 Non Patent Literature 3: Kenji HATANAKA, Cyclic Stress-Strain Properties and Low-Cycle Fatigue Life of Metal Material, Journal of the Japan Society of Mechanical Engineers (Edition A), 50, (1984), 831.

Summary of Invention

Technical Problem

[0021] Cast material has been widely used in buildings and civil structures. The reason is that there are great advantages that an object having a complicated shape, a large object, or the like can be easily made at a low cost; a geometrically complicated variable cross-sectional shape member (a plate thickness and a plate width are variable) can be manufactured without frequently using welding (a column, a joint, a node, and the like), and man-hour decreases (an assembly accuracy is improved), and thus, the cost can be decreased; in a case where casting is applied (for example, die-casting or the like), the casting can be used almost without post-processing; and an assembly accuracy is improved, and mass production can be performed as long as the lifetime of a mold is maintained. Further, in a case where the cast material is used in a column or the like, there are great practical merits that it is possible to arrange a complicated joining portion with respect to a beam, and to provide architecturally various two-dimensional plans or the like, and thus, the cast material has been utilized in the right places.

[0022] However, the cast material has a cast defect such as segregation, a void, and an inclusion, and thus, the fatigue properties of the cast material are obviously degraded compared to a rolling material or the like having the same composition, and a use range is limited, for example, in a building member, the cast material can be used for only a member which is used in the elastic range even during a large earthquake.

[0023] From the background described above, the present invention is to solve the conventional problems and focuses on unique deformation behavior of the Fe-Mn-Si-based alloy, and thus, an object of the present invention is to provide a new cast material having excellent low-cycle fatigue properties which is useful as a structural building material or the like.

Solution to Problem

[0024] That is, the Fe-Mn-Si-based alloy cast material of the present invention is characterized by the followings.

[0025] In one aspect of the present invention, an Fe-Mn-Si-based cast alloy contains Mn and Si as essential additive elements, and one or more of Cr, Ni, Al, and C as an optional additive element, the Fe-Mn-Si-based cast alloy consisting

of a component composition of:

$$5 \text{ mass\%} \leq \text{Mn} \leq 35 \text{ mass\%},$$

$$1.5 \text{ mass\%} \leq \text{Si} \leq 6.5 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Ni} \leq 15 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Al} \leq 3 \text{ mass\%},$$

and

$$0 \text{ mass\%} \leq \text{C} \leq 0.4 \text{ mass\%},$$

with the balance being Fe and inevitable impurities, in which the component composition satisfies the following conditions of Formula (a) and Formula (b),

$$(a): \quad 37 < [\% \text{Mn}] + 0.3[\% \text{Si}] + 0.7[\% \text{Cr}] + 2.4[\% \text{Ni}] + 5.2[\% \text{Al}] + 28[\% \text{C}] < 45,$$

and

$$(b): \quad [\% \text{Ni}] + 30[\% \text{C}] + 0.5[\% \text{Mn}] > 0.75[\% \text{Cr}] + 1.125[\% \text{Si}] + 2[\% \text{Al}].$$

(In the formulae, [%Mn], [%Si], [%Cr], [%Ni], [%Al], and [%C] represent contents (mass%) of Mn, Si, Cr, Ni, Al, and C, respectively.)

[0026] In another aspect of the present invention, in the Fe-Mn-Si-based alloy cast material, the component composition is,

$$25 \text{ mass\%} \leq \text{Mn} \leq 35 \text{ mass\%},$$

$$2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Cr} \leq 8 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Al} \leq 3 \text{ mass\%},$$

and

$$0 \text{ mass\%} \leq \text{C} \leq 0.2 \text{ mass\%},$$

with the balance being Fe and inevitable impurities.

[0027] In another aspect of the present invention, in the Fe-Mn-Si-based cast alloy, the component composition is,

5 $10 \text{ mass\%} \leq \text{Mn} \leq 20 \text{ mass\%},$

$2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%},$

10 $5 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%},$

15 $5 \text{ mass\%} \leq \text{Ni} \leq 10 \text{ mass\%},$

and

20 $0 \text{ mass\%} \leq \text{C} \leq 0.2 \text{ mass\%},$

with the balance being Fe and inevitable impurities.

[0028] In another aspect of the present invention, in the Fe-Mn-Si-based cast alloy, the component composition is,

25 $5 \text{ mass\%} \leq \text{Mn} \leq 8 \text{ mass\%},$

$2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%},$

30 $9 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%},$

35 $9 \text{ mass\%} \leq \text{Ni} \leq 15 \text{ mass\%},$

and

40 $0 \text{ mass\%} \leq \text{C} \leq 0.4 \text{ mass\%},$

with the balance being Fe and inevitable impurities.

[0029] In another aspect of the present invention, a seismic damping device using the Fe-Mn-Si-based cast alloy is provided.

45 **[0030]** In another aspect of the present invention, a steel structure or a reinforced concrete structure using the Fe-Mn-Si-based cast alloy is provided.

[0031] In another aspect of the present invention, a cast material for a seismic damping device using the Fe-Mn-Si-based cast alloy is provided.

50 **[0032]** In another aspect of the present invention, use of the Fe-Mn-Si-based cast alloy for a seismic damping device, a steel structure, or a reinforced concrete structure is provided.

Advantageous Effects of Invention

55 **[0033]** According to the present invention, a cast product having extremely excellent fatigue properties is provided. That is, in the present invention, as specifically described in examples described below, a cast material is realized in which fatigue resistance performance that is comparable or superior to (three times or more) that of a general steel material is obtained. This is performance greatly exceeding that of the conventional low-yield-point steel, as a damping material. Even in a case where the Fe-Mn-Si-based cast alloy of the present invention involves defects of usually

conceivable size, an influence on various performance degradations (stability, deformation performance, fatigue durability, and the like) is minimized, and thus, a material strength can be effectively utilized.

[0034] Therefore, the Fe-Mn-Si-based cast alloy of the present invention can be used in an elastic-plastic region beyond the conventional concept, and can be widely applied to not only a column, a beam, a cast steel node, and the like that are subjected to large deformation during a large earthquake, but also a damping member.

Brief Description of Drawings

[0035]

Fig. 1 is a schematic view of a structure that improves a low-cycle fatigue life of an Fe-Mn-Si-based cast alloy.

Figs. 2(a)-2(c) show a structure before a low-cycle fatigue test of Fe-15Mn-10Cr-8Ni-4Si cast alloy. Fig. 2(a) is a phase map (White: γ Phase, Gray: ε Phase, and Charcoal: α' Phase), Fig. 2(b) is a γ phase inverse pole figure map, and Fig. 2(c) is a γ phase 001 pole figure.

Figs. 3(a)-3(e) show a deformation structure after low-cycle fatigue fracture of Fe-15Mn-10Cr-8Ni-4Si cast alloy. Fig. 3(a) is a phase map (White: γ Phase and Gray: ε Phase), Fig. 3(b) is a γ phase inverse pole figure map, Fig. 3(c) is an ε phase inverse pole figure map, Fig. 3(d) is a γ phase 001 pole figure, and Fig. 3(e) is an ε phase 0001 pole figure.

Figs. 4(a) and 4(b) show a formation of a shrinkage cavity in a deformation structure after low-cycle fatigue fracture of Fe-15Mn-10Cr-8Ni-4Si cast alloy. Fig. 4(a) is a broad phase map, and Fig. 4(b) is a phase map around shrinkage cavity (White: γ Phase and Gray: ε Phase).

Figs. 5(a)-5(f) show an element concentration distribution around shrinkage cavity in Fe-15Mn-10Cr-8Ni-4Si cast alloy. Fig. 5(a) is a secondary electron image, Fig. 5(b) is Fe element concentration distribution, Fig. 5(c) is Mn element concentration distribution, Fig. 5(d) is Ni element concentration distribution, Fig. 5(e) is Cr element concentration distribution, and Fig. 5(f) is Si element concentration distribution.

Figs. 6(a) and 6(b) show relationship between redistribution of each component element and the solid phase fraction in Fe-15Mn-10Cr-8Ni-4Si alloy calculated by using thermodynamic calculation software Pandat. Fig. 6(a) is an approximation based on Lever equation and Fig. 6(b) is an approximation based on Scheil equation.

Description of Embodiments

[0036] As described above, in order to develop a cast material having an excellent low-cycle fatigue life, the present invention focuses on unique deformation behavior of an Fe-Mn-Si-based alloy. The present invention is accomplished by conducting studies from the viewpoint that, although a cast defect such as a void or an inclusion is a weak point of the cast material in regard to metal fatigue, if a fatigue resistance mechanism can be activated by reversible martensitic transformation between a γ austenite phase and an ε martensite phase without occurring a fatigue crack due to such a cast defect, it is expected that the low-cycle fatigue life is improved even in the cast material.

[0037] That is, in one embodiment of the present invention, an Fe-Mn-Si-based cast alloy contains Fe as a main component and Mn and Si as essential additive elements in its component composition, a metal structure after casting has a γ austenitic phase of 85 volume% or more, and the γ austenitic phase includes dendritic segregation of elemental components, and an inevitable void or inclusion is dispersed and formed in a last solidifying part between the dendritic segregations, in which a deformation structure change at the time of cyclic tension-compression deformation occurs due to reversible martensitic transformation between the γ austenite phase and the ε martensite phase of the dendritic segregation portion, the occurrence of a fatigue crack from the void or the inclusion that is dispersed and formed in the last solidifying part between the dendritic segregations is suppressed, and a low-cycle fatigue life at an amplitude of ± 1 % is 3000 cycles or more.

[0038] The low-cycle fatigue life is affected not only by a material or a strain amplitude, but also by various conditions such as a sample shape, a surface state, a defect, and an accuracy of deformation control, and thus, there are many cases where a value lower than the original performance of the material is obtained due to a cause other than a condition that can be controlled by an experimenter, and a statistical variation is also large. Thus, even in the case of extremely carefully considering an experiment condition, a low-cycle fatigue life at an amplitude of ± 1 % of a commercially available steel material reported in various literatures is 2000 cycles at most regardless of the material (Non Patent Literature 3). The cast material having a cast defect generally has a low-cycle fatigue life that is significantly lower than the low-cycle fatigue life described above, and thus, in the present invention, 3000 cycles obtained by multiplying 2000 cycles by a safety ratio of 1.5 is the basis of a low-cycle fatigue life that is significantly excellent compared to that of the conventional material.

[0039] In the present invention, in the Fe-Mn-Si-based cast alloy, segregation due to component condensation into a liquid phase during solidification is positively utilized, and thus, the fatigue resistance mechanism due to the martensitic

transformation between the reversible γ austenite phase and the ε martensite phase is activated without occurring a fatigue crack due to a cast defect. That is, in a dendritic segregation portion which is solidified precedingly, the fatigue resistance mechanism due to the martensitic transformation between the reversible γ austenite phase and the ε martensite phase is activated on a slip plane of the γ phase that is inclined with respect to a tension-compression deformation axis, and a state is formed in which a γ phase in the last solidifying part between the dendritic segregations is not deformed. Accordingly, the occurrence of a crack due to a void or an inclusion included in the last solidifying part is suppressed.

[0040] A plastic deformation mechanism in a γ austenite alloy has various forms such as a slip motion of a lattice dislocation that is a plastic deformation mechanism of a general metal, a slip motion of an extended dislocation in which the lattice dislocation is moved by being separated into two partial dislocations and a stacking-fault in between, γ deformation twinning, ε martensitic transformation, and α' martensitic transformation, and in general, plural plastic deformation mechanisms are simultaneously expressed.

[0041] In the Fe-Mn-Si-based cast alloy of the present invention, a blending ratio of Mn, Si, and other additive elements is adjusted, and thus, a state is formed in which a structural change due to tension-compression plastic deformation reversibly progresses by bidirectional martensitic transformation that occurs between the γ austenite phase and the ε martensite phase, cyclic hardening is suppressed and the number of cycles to fracture increases. As illustrated in a schematic view of a structure that improves a low-cycle fatigue life of an Fe-Mn-Si-based cast alloy of Fig. 1, a state is formed in which such reversible plastic deformation progresses only in the dendritic segregation portion, but the last solidifying part between the dendritic segregations in which there are many voids formed due to solidification shrinkage, or many inclusions formed due to component condensation remains as the γ phase without contributing to deformation, and thus, the occurrence of a crack due to the void or the inclusion is suppressed. The ε phase generated by the martensitic transformation from the γ phase by initial deformation is arranged in parallel in a state where a plate surface is inclined with respect to a tension-compression axis, and thus, slip deformation that occurs on a crystallographic basal surface ($\parallel$ the plate surface) of the ε phase, the bidirectional martensitic transformation between the γ phase and the ε phase reversibly occurs with respect to tension-compression deformation, and it is possible to delay the occurrence or the propagation of the crack without being affected by the void or the inclusion at all.

[0042] For this reason, it is desirable that a state before deformation is a γ austenite single-phase, the plastic deformation mechanism of the dendritic segregation portion mainly progresses by the ε martensitic transformation, and the component condensation of the last solidifying part occurs on a side where the ε martensitic transformation is suppressed. At this time, a deformation twinning, a lattice dislocation slip, and an extended dislocation slip, that inevitably occur in accordance with the ε martensitic transformation of the dendritic segregation portion, may be included partially, but the occurrence of the α' martensitic transformation is necessary to suppress because the α' martensitic transformation noticeably hardens an alloy.

[0043] The γ austenite single-phase is desirable as the state before the deformation, and a small amount of ε martensitic phase, δ ferritic phase, and α' martensitic phase may be included. There is a case where an alloy adjusted to a state in which the ε martensitic transformation is easily induced by deformation incidentally forms the ε martensitic phase by a temperature change in the environment, the influence of processing, or the like.

[0044] The ε martensitic phase, the δ ferritic phase, and the α' martensitic phase which are incidentally formed may become a barrier with respect to the growth of a deformation-induced ε martensitic phase generated on a specific crystal surface inclined with respect to the tension-compression axis, and can be a fatigue crack generation source, and thus, in order to prevent such a problem, a volume ratio of main phase γ austenite is set to be 85 volume% or more.

[0045] In addition, it is concerned that in the cast material, in addition to the cast defect such as the void or the inclusion, a precipitate that may be incidentally formed in a multicomponent system causes the occurrence of a fatigue crack. However, in a case where such a precipitate is also formed due to the component condensation with respect to the last solidifying, as with the void or the inclusion, a peripheral γ phase is not particularly subjected to the deformation, and thus, there is no concern that the precipitate becomes a crack generation source.

[0046] As it is understood from the features of the present invention, the term of the "cast material" of the present invention does not include a cast material obtained by forging or rolling an ingot after casting or a cast material obtained by changing a crystal phase with a heat treatment.

[0047] A crystal structure or a change thereof in the cast material of the present invention is confirmed by general analysis means such as a scanning electron microscope and a back scattering electron diffraction method.

[0048] Hereinafter, component elements configuring the Fe-Mn-Si-based alloy cast material of the present invention will be described. In the present invention, the term "Fe-Mn-Si-based alloy" indicates an alloy containing iron (Fe) as a main component, and manganese (Mn) and silicon (Si).

[0049] Manganese (Mn) is an essential component element that majorly affects the plastic deformation mechanism of the Fe-Mn-Si-based alloy. Mn has effects of stabilizing a γ austenitic phase in an iron-based alloy, and of reducing a stacking-fault energy to form a state in which a martensitic transformation to an ε martensitic phase from a γ austenitic phase easily occurs.

[0050] Therefore, in the cast material of the present invention, by adjusting the additive amount of Mn, the ε martensitic

transformation from deformation-induced γ and reverse transformation thereof alternately occur during a tension-compression plastic deformation, the formation of an α' martensitic phase is suppressed, and it is possible to improve fatigue properties.

[0051] When the additive amount of Mn is greater than 35 mass%, the γ phase is antiferromagnetized, and is strongly stabilized even when additive amounts of other elements are adjusted in any way, and thus, ε martensite is not obtained. In addition, when the additive amount of Mn is less than 5 mass%, there is a case where the α' martensite phase harmful to fatigue properties is inevitably formed. For these reasons, in the present invention, the additive amount of Mn is in a range of $5 \text{ mass\%} \leq \text{Mn} \leq 35 \text{ mass\%}$.

[0052] In addition, as described in Patent Literature 1, Cr, Ni, and Al may be added as an element having an alternative effect of Mn, and the effects of Mn, Cr, Ni, and Al on the plastic deformation mechanism can be represented by content (mass%) of Mn (Mn equivalent weight: $[\% \text{Mn}]_{\text{eq}}$) having the equivalent effect. In the present invention, a relational expression is modified in consideration of the effect of component elements Si and C, and the Mn equivalent weight is represented by the following Formula (1) by using the additive amount (mass%) of each of the component elements.

$$\begin{aligned} \text{Mn equivalent weight } ([\% \text{Mn}]_{\text{eq}}) = & [\% \text{Mn}] + 0.3[\% \text{Si}] + 0.7[\% \text{Cr}] + 2.4[\% \text{Ni}] \\ & + 5.2[\% \text{Al}] + 28[\% \text{C}] \quad (1) \end{aligned}$$

In the above formula, $[\% \text{Mn}]$, $[\% \text{Si}]$, $[\% \text{Al}]$, $[\% \text{Cr}]$, $[\% \text{Ni}]$, and $[\% \text{C}]$ represent contents (mass%) of Mn, Si, Al, Cr, Ni, and C as chemical components of the Fe-Mn-Si-based cast alloy, respectively.

[0053] In addition, in the present invention, the range of Mn equivalent weight for exhibiting bidirectional martensitic transformation between the γ austenitic phase and the ε martensitic phase is set to a condition represented by the following Formula (2).

$$37 < [\% \text{Mn}]_{\text{eq}} < 45 \quad (2)$$

When the Mn equivalent weight is 37 or less, thermodynamic stability of the ε martensitic phase extremely increases, and thus, the γ phase between the dendritic segregations is also subjected to the ε martensitic transformation, a probability that a fatigue crack occurs from a void or an inclusion increases, and the low-cycle fatigue life decreases.

[0054] In addition, when the Mn equivalent weight is 45 or more, the stacking-fault energy increases, the ε martensite is not formed in the dendritic segregation portion, the fatigue resistance mechanism is not activated, and the low-cycle fatigue life decreases.

[0055] On the other hand, in Patent Literature 1 and Non Patent Literatures 1 and 2, it is disclosed that silicon (Si) that is another essential component element in the Fe-Mn-Si-based alloy of the present invention hardly affects the Mn equivalent weight, but improves the reversibility of the bidirectional martensite transformation between the γ austenite phase and the ε martensite phase. The function of Si is effective even in a cast material, but in a case where Si is excessively added, the number of cycles to fracture of the cast material decreases. In particular, in a case where Si of greater than 6.5 mass% is added, the alloy is noticeably hardened, and thus, there is a case where a stress amplitude of the cyclic tension-compression deformation increases, or a silicide-based intermetallic compound is formed, and thus, the alloy becomes brittle. In addition, when the additive amount of Si is less than 1.5 mass%, the dislocations alternately slip, and are arranged again into the shape of a cell, and crack initiation and propagation are accelerated. For these reasons, in the present invention, the additive amount of Si is $1.5 \text{ mass\%} \leq \text{Si} \leq 6.5 \text{ mass\%}$, and is more preferably $2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%}$. In particular, in a case where the additive amount of Si is close to 4 mass%, the function of Si is most effectively exhibited.

[0056] In addition, in the Fe-Mn-Si-based alloy of the present invention, Cr, Ni, Al, and C may be added as an optional component element.

[0057] Chromium (Cr) is an element that reduces the stacking-fault energy of the γ austenitic phase and promotes the martensitic transformation to the ε martensitic phase, thereby improving the fatigue properties of the cast material of the present invention. In addition, Cr also contributes to improve of corrosion resistance and high-temperature oxidation resistance. However, when the additive amount of Cr is greater than 15 mass%, ferrite or the α' martensite is likely to form, and the low-cycle fatigue life decreases. For these reasons, in the present invention, the additive amount of Cr is in a range of $0 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%}$.

[0058] Nickel (Ni) is an alternative element of Mn for the austenite stabilizing behavior. In particular, when the additive amount of Mn is less than 20 mass%, Ni of 2 mass% or more is added as an austenite stabilizing element, and thereby, it is possible to obtain the γ austenitic single-phase, which is in a state before the deformation. On the other hand, when

the additive amount of Ni is greater than 15 mass%, Fe-Ni silicide or Ni-Mn silicide is remarkably formed, and the alloy becomes brittle. For these reasons, in the present invention, the additive amount of Ni is in a range of $0 \text{ mass\%} \leq \text{Ni} \leq 15 \text{ mass\%}$.

[0059] Aluminum (Al) is an element having an influence on the Mn equivalent weight by factor 5.2, as represented in Formula (1) described above, and thus, may be added as an alternative element of Mn. However, when the additive amount of Al is greater than 3 mass%, a decrease in the low-cycle life is likely to occur due to the formation of ferrite. In addition, in a case where a heat treatment is performed in the atmosphere, there is also a possibility that nitride is formed since Al has high affinity with nitrogen, and the alloy becomes brittle. As described above, even a small amount of Al is effective in the adjustment of the Mn equivalent weight, but in a case where Al is excessively added, there is also an adverse effect, and thus, in the present invention, the additive amount of Al is in a range of $0 \text{ mass\%} \leq \text{Al} \leq 3 \text{ mass\%}$.

[0060] Carbon (C) is an alternative element of Mn for the austenite stabilizing behavior, but when the additive amount of C is greater than 0.4 mass%, a carbide is formed, and the low-cycle fatigue life decreases. For these reasons, in the present invention, the additive amount of C is in a range of $0 \text{ mass\%} \leq \text{C} \leq 0.4 \text{ mass\%}$.

[0061] In the present invention, in the additive amount of Mn and Si as essential component elements, and Cr, Ni, Al, and C as an optional component element, it is important to adjust a balance between the total amount of Ni, C, and Mn which are austenite stabilizing element and the total amount of Cr, Si, and Al which are ferrite stabilizing element such that a metal structure before the deformation becomes a γ austenitic single-phase. As the concentration of the ferrite stabilizing elements is high and the concentration of the austenite stabilizing elements is low, a δ ferrite phase is likely to form, and an α' martensite phase is likely to form when both of the concentration of the ferrite stabilizing elements and the concentration of the austenite stabilizing elements are low.

[0062] From experimental results by the inventors, in the Fe-Mn-Si-based alloy of the present invention, in a state after casting, or in a case where water quenching or gradual cooling is performed after a homogenization heat treatment at 1000°C for a time of 1 minute or more after casting, it has been found that the additive amount of component elements satisfied conditions of the following Formula (3) so as to suppress the formation of the δ ferrite phase and to make the γ austenite single-phase.

$$[\% \text{Ni}] + 30[\% \text{C}] + 0.5[\% \text{Mn}] > 0.75[\% \text{Cr}] + 1.125[\% \text{Si}] + 2[\% \text{Al}] \quad (3)$$

In the formula, [%Ni], [%C], [%Mn], [%Cr], [%Si], and [%Al] represent contents (mass%) of Ni, C, Mn, Cr, Si, and Al as chemical components of the Fe-Mn-Si-based cast alloy, respectively.

[0063] Based on the above description, examples of a preferred embodiment of the component composition of the Fe-Mn-Si-based cast alloy of the present invention are as follows.

<Composition 1>

[0064] Fe is contained as a main component, Mn and Si are contained as essential component elements, and one or more of Cr, Ni, Al, and C are contained as an optional component element, a component composition is,

$$5 \text{ mass\%} \leq \text{Mn} \leq 35 \text{ mass\%},$$

$$1.5 \text{ mass\%} \leq \text{Si} \leq 6.5 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Ni} \leq 15 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Al} \leq 3 \text{ mass\%},$$

and

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$$0 \text{ mass\%} \leq C \leq 0.4 \text{ mass\%},$$

with the balance being Fe and inevitable impurities, and the component composition satisfies the following conditions of Formula (a) and Formula (b),

$$(a): \quad 37 < [\%Mn] + 0.3[\%Si] + 0.7[\%Cr] + 2.4[\%Ni] + 5.2[\%Al] + 28[\%C] < 45,$$

and

$$(b): \quad [\%Ni] + 30[\%C] + 0.5[\%Mn] > 0.75[\%Cr] + 1.125[\%Si] + 2[\%Al].$$

(In the formulae, [%Mn], [%Si], [%Cr], [%Ni], [%Al], and [%C] represent contents (mass%) of Mn, Si, Cr, Ni, Al, and C, respectively.)

<Composition 2>

[0065] Fe is contained as a main component, Mn and Si are contained as essential component elements, and one or more of Cr, Al, and C are contained as an optional component element, a component composition is,

$$25 \text{ mass\%} \leq Mn \leq 35 \text{ mass\%},$$

$$2 \text{ mass\%} \leq Si \leq 6 \text{ mass\%},$$

$$0 \text{ mass\%} \leq Cr \leq 8 \text{ mass\%},$$

$$0 \text{ mass\%} \leq Al \leq 3 \text{ mass\%},$$

and

$$0 \text{ mass\%} \leq C \leq 0.2 \text{ mass\%},$$

with the balance being Fe and inevitable impurities, and the component composition satisfies the following conditions of Formula (a') and Formula (b'),

$$(a'): \quad 37 < [\%Mn] + 0.3[\%Si] + 0.7[\%Cr] + 5.2[\%Al] + 28[\%C] < 45,$$

and

$$(b'): \quad 30[\%C] + 0.5[\%Mn] > 0.75[\%Cr] + 1.125[\%Si] + 2[\%Al].$$

(In the formula, [%Mn], [%Si], [%Cr], [%Al], and [%C] represent contents (mass%) of Mn, Si, Cr, Al, and C, respectively.)

<Composition 3>

[0066] Fe is contained as a main component, Mn and Si are contained as essential component elements, and one or

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more of Cr, Ni, and C are contained as an optional component element, a component composition is,

$$10 \text{ mass\%} \leq \text{Mn} \leq 20 \text{ mass\%},$$

$$2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%},$$

$$5 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%},$$

$$5 \text{ mass\%} \leq \text{Ni} \leq 10 \text{ mass\%},$$

and

$$0 \text{ mass\%} \leq \text{C} \leq 0.2 \text{ mass\%},$$

with the balance being Fe and inevitable impurities, and the component composition satisfies the following conditions of Formula (a") and Formula (b"),

$$(a''): 37 < [\% \text{Mn}] + 0.3[\% \text{Si}] + 0.7[\% \text{Cr}] + 2.4[\% \text{Ni}] + 28[\% \text{C}] < 45,$$

and

$$(b''): [\% \text{Ni}] + 30[\% \text{C}] + 0.5[\% \text{Mn}] > 0.75[\% \text{Cr}] + 1.125[\% \text{Si}].$$

(In the formula, [%Mn], [%Si], [%Cr], [%Ni], and [%C] represent contents (mass%) of Mn, Si, Cr, Ni, and C, respectively.)

<Composition 4>

[0067] Fe is contained as a main component, Mn and Si are contained as essential component elements, and one or more of Cr, Ni, and C are contained as an optional component element, a component composition is,

$$5 \text{ mass\%} \leq \text{Mn} \leq 8 \text{ mass\%},$$

$$2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%},$$

$$9 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%},$$

$$9 \text{ mass\%} \leq \text{Ni} \leq 15 \text{ mass\%},$$

and

$$0 \text{ mass\%} \leq \text{C} \leq 0.4 \text{ mass\%},$$

with the balance being Fe and inevitable impurities, and the component composition satisfies the following conditions of Formula (a") and Formula (b"),

$$(a''): 37 < [\%Mn] + 0.3[\%Si] + 0.7[\%Cr] + 2.4[\%Ni] + 28[\%C] < 45,$$

and

$$(b''): [\%Ni] + 30[\%C] + 0.5[\%Mn] > 0.75[\%Cr] + 1.125[\%Si].$$

(In the expression, [%Mn], [%Si], [%Cr], [%Ni], and [%C] represent contents (mass%) of Mn, Si, Cr, Ni, and C, respectively.)

[0068] The composition 1 satisfies the conditions of Formula (1) and Formula (2), and, as described above, is a preferred embodiment of the composition of the Fe-Mn-Si-based alloy of the present invention which is determined by considering the influence of each of the component elements on a casting structure or a cyclic deformation structure.

[0069] The composition 2 represents a component range in which a low-cycle fatigue life improvement effect is most effectively exhibited by setting the additive amount of Mn to be $25 \text{ mass}\% \leq \text{Mn} \leq 35 \text{ mass}\%$, and by setting the additive amount of Si to be $2 \text{ mass}\% \leq \text{Si} \leq 6 \text{ mass}\%$. In this case, the additive amounts of the other component elements for satisfying the conditions of Formula (1) and Formula (2) are $0 \text{ mass}\% \leq \text{Cr} \leq 8 \text{ mass}\%$, $0 \text{ mass}\% \leq \text{Al} \leq 3 \text{ mass}\%$, and $0 \text{ mass}\% \leq \text{C} \leq 0.2 \text{ mass}\%$.

[0070] The composition 3 represents a component range for facilitating electric furnace dissolution by considering a mass production from a more practical viewpoint, and by comparatively decreasing the additive amount of Mn to be $10 \text{ mass}\% \leq \text{Mn} \leq 20 \text{ mass}\%$. The ranges of the additive amounts of the other component elements are determined by the conditions of Formula (1) and Formula (2).

[0071] The composition 4 represents a component range for obtaining corrosion resistance improvement effect by further decreasing the additive amount of Mn, and by increasing the additive amount of Cr and Ni. The ranges of the additive amounts of the other component elements are determined by the conditions of Formula (1) and Formula (2).

[0072] The Fe-Mn-Si-based cast alloy of the present invention described above may be cast by melting a metal component of a raw material.

[0073] In addition, the Fe-Mn-Si-based cast alloy of the present invention has excellent fatigue properties, and thus, can be applied to a use application as a cast member that can be used not only in a conventional elastic region but also in a plastic region. Specifically, for example, the Fe-Mn-Si-based cast alloy of the present invention is particularly suitable for a use application as a cast material for a seismic damping device. In addition, a seismic damping device, a steel structure, and a reinforced concrete structure using the Fe-Mn-Si-based cast alloy of the present invention have a significantly excellent low-cycle fatigue life, compared to the conventional material.

Examples

[0074] The present invention will be described below in more detail based on Examples, but the present invention is not limited to these Examples.

[0075] An alloy having a component composition of Mn: 15 mass%, Cr: 10 mass%, Ni: 8 mass%, Si: 4 mass%, the balance being Fe, and inevitable impurities (hereinafter, referred to as an Fe-15Mn-10Cr-8Ni-4Si alloy) was prepared by high frequency vacuum induction melting process. A low-cycle fatigue test piece having 8 mm-diameter parallel portion was prepared from the Fe-15Mn-10Cr-8Ni-4Si alloy ingot by lathe working, in a direction in which the deformation axis is orthogonal to columnar crystals which were grown during casting. The test piece was subjected to a tension-compression strain control low-cycle fatigue test at an amplitude of $\pm 1\%$ with a triangle wave of 0.4%/second under an atmosphere of room temperature, and a structure before and after the fatigue test was observed by a scanning electron microscope-back scattering electron diffraction method. In addition, phase identification was performed by X ray diffraction, and a volume fraction of a phase constituting the material was evaluated by Rietveld analysis.

[0076] Figs. 2(a)-2(c) show the structure before the low-cycle fatigue test of the Fe-15Mn-10Cr-8Ni-4Si cast alloy I (as-cast alloy) analyzed by a back scattering electron diffraction method. Fig. 2(a) is the phase map, and illustrates the state of distribution in which the γ phase is represented by a white color, the ε phase is represented by a gray color, and the α' phase is represented by a charcoal color. In the structure of Fig. 2(a), the white γ austenitic phase is dominant, and the gray ε martensitic phase is slightly scattered, but the volume ratio thereof is less than 3%. In addition, the γ phase is grown into the shape of a column in a vertical direction. Fig. 2(b) is the γ phase inverse pole figure map, and in this figure, as illustrated in the direction of a cubic pattern, columnar crystals are grown along a 001 direction of the γ phase. This is general characteristics observed in the casting structure of a face-centered lattice structure (FCC) metal. Fig. 2(c) is the γ phase 001 pole figure, and it is confirmed that the 001 direction is parallel to the columnar crystal growth direction.

[0077] Figs. 3(a)-3(e) show the deformation structure after a low-cycle fatigue fracture of the Fe-15Mn-10Cr-8Ni-4Si cast alloy. From the phase map of Fig. 3(a), it can be seen that the ϵ phase (gray) is formed in the γ phase (white) during the cyclic tension-compression deformations. The remaining γ phase is a columnar crystal growing along the 001 direction (Figs. 3(b) and 3(d)), and, from the pole figure (Fig. 3(e)), it can be seen that the 0001 basal surface of the dendritic ϵ phase formed therein (Fig. 3(c)) is also distributed in a specific direction range. According to Non Patent Literature 2, even when an ϵ phase is formed once, in a case where a deformation direction is inverted, then the ϵ phase disappears by the reverse transformation, and these formation / disappearance are repeated, but the ϵ phase is gradually stabilized during the cyclic tension-compression deformation and the cumulative volume ratio slowly increases.

[0078] Fig. 4(a) shows the solidification shrinkage referred to as a shrinkage cavity, as a state of distribution (a broad phase map) in the structure after the low-cycle fatigue fracture of the Fe-15Mn-10Cr-8Ni-4Si cast alloy, and Fig. 4(b) is the enlarged view around the shrinkage cavity. The remaining γ phase is formed around the void, and a void is hardly observed in a portion where the ϵ phase is generated. In addition, it can be seen that the dendritic ϵ phase is formed by stacking thin plate-like ϵ phases.

[0079] Structure analysis results described above proves that the material subjected to the casting of the Fe-15Mn-10Cr-8Ni-4Si alloy has a structure and a deformation manner illustrated in the schematic view of Fig. 1.

[0080] Figs. 5(a)-5(f) are the results of analyzing the distribution of element concentration around the shrinkage cavity in Fig. 4(b) by energy dispersive X ray spectrometry. Figs. 5(a) to 5(f) show that a region in which Fe and Cr are concentrated and a region in which Mn, Ni, and Si are concentrated are generated by the solidification segregation.

[0081] Figs. 6(a) and 6(b) are diagrams illustrating a liquid phase condensation tendency of each of the component elements in the Fe-15Mn-10Cr-8Ni-4Si alloy calculated by using thermodynamic calculation software Pandat. Fig. 6(a) shows a model based on Lever equation assuming an element diffusion sufficient for realizing a thermodynamic balance state, and Fig. 6(b) shows a model based on Scheil equation assuming that a liquid phase is in a uniform concentration without diffusion. By using such models, when it is assumed that an actual material is in an intermediate state of these models, it is possible to discuss whether an element is likely to be condensed into a liquid phase in a solid-liquid coexistence state in the middle of the solidification. From the analysis result thereof, it can be seen that Mn and Si have a strong liquid phase condensation tendency, that is, are easily condensed to a last solidifying part.

[0082] That is, it can be seen from the segregation of the component elements illustrated in Figs. 5(a) to 5(f) that the region in which Fe and Cr are concentrated is a tip end of an arm of the dendritic region which is solidified precedingly, and the region in which Mn, Ni, and Si are concentrated is the last solidifying part. In addition, from the comparison with Fig. 4, it can be seen that the ϵ martensitic phase is formed only in the region in which Fe and Cr are concentrated, and the region in which Mn, Ni, and Si are concentrated is the γ austenitic phase as it is without being subjected to ϵ transformation by the deformation. The void caused by the solidification shrinkage is formed in the region in which Mn, Ni, and Si are concentrated in the last solidifying part, and thus, is not subjected to the shear deformation of the ϵ transformation, and therefore, it is considered that in the Fe-15Mn-10Cr-8Ni-4Si cast alloy, as illustrated in the schematic view of Fig. 1, a mechanism is realized in which the void remains as not being deformed under the cyclic deformation even though it basically tends to be a generating point of a crack.

[0083] The following Table 1 shows low-cycle fatigue lives measured with regard to test pieces prepared by the same method from Fe-Mn-Si-based alloy ingots of each of the component compositions, by tension-compression strain control at an amplitude of $\pm 1\%$ with a triangle wave of 0.4%/second under an atmosphere of room temperature.

[Table 1]

	Component Composition						Composition Condition			Volume Fraction of γ Phase after Casting	$\pm 1\%$ Low-Cycle Fatigue Life	
	Mn	Si	Al	Cr	Ni	C	Formula (2) 37<(Mn) eq<45	Formula (3)				
								(Left side)> (Right side)	Satisfiability			
Example 1	15	4	0	10	8	0	42.4	15.5	12.0	○	100	8790
Example 2	30	4	2	0	0	0	41.6	15.0	8.5	○	100	8010
Example 3	27	4	2	5	0	0.04	43.2	13.5	12.3	○	100	5200
Example 4	33	4	1.5	0	0	0	42.0	16.5	7.5	○	100	5700
Example 5	15	2	0	10	8	0	41.8	15.5	9.8	○	100	3120
Example 6	15	6	0	10	8	0	43.0	15.5	14.3	○	100	4523
Example 7	17	4	0	10	7	0.03	42.8	15.5	12.0	○	100	7250
Example 8	18	3	0	8	6	0.05	40.3	15.0	9.4	○	100	7830
Example 9	13	4	0	10	8	0.05	41.8	14.5	12.0	○	100	7770
Example 10	12	4	0	12	8	0.05	42.2	14.0	13.5	○	100	7320
Example 11	5	4	0	12	12	0	43.4	14.5	13.5	○	100	3052
Comparative Example 1	30	6	0	0	0	0	31.8	15.0	6.8	○	91	1925
Comparative Example 2	30	3	3	0	0	0	46.5	15.0	9.4	○	100	2012
Comparative Example 3	37	4	0	0	0	0	38.2	18.5	4.5	○	100	896
Comparative Example 4	30	2	4	0	0	0	51.4	15.0	10.3	○	100	1523
Comparative Example 5	15	0	0	10	8	0	41.2	15.5	7.5	○	100	2250
Comparative Example 6	15	7	0	10	8	0.1	46.1	15.5	15.4	○	93	950
Comparative Example 7	10	4	0	12	8	0	38.8	13.0	13.5	×	91.5	1985

(continued)

	Component Composition						Composition Condition			Volume Fraction of γ Phase after Casting	$\pm 1\%$ Low-Cycle Fatigue Life
	Mn	Si	Al	Cr	Ni	C	Formula (2)	Formula (3)			
							37<(Mn) eq<45	(Left side)> (Right side)	Satisfiability		
Comparative Example 8	5	4	0	18	9	0	40.4	11.5	18.0	×	2875

[0084] The cast materials of Examples 1 to 11 have common characteristics that the γ austenitic phase has a volume ratio of 85% or more before the deformation, and the volume ratio of the ε martensitic phase increases after the fatigue fracture, and the low-cycle fatigue life of all of the cast materials of Examples 1 to 11 is greater than 3000 cycles. These results demonstrate that the reversible martensitic transformation between the γ austenitic phase and the ε martensitic phase is effective in the improvement of the low-cycle fatigue life.

[0085] On the other hand, in the cast materials of Comparative Examples 1 to 8, the plastic deformation occurs in accordance with the slip deformation of the γ phase or the α' martensitic transformation, and thus, the fatigue resistance mechanism of the reversible martensitic transformation between the γ austenite phase and the ε martensite phase is not effectively activated, and therefore, the low-cycle fatigue life is less than 3000 cycles.

[0086] In addition, it has been confirmed that, in a case where the cast materials of the Fe-15Mn-10Cr-8Ni-4Si alloy of Example 1 and the Fe-30Mn-4Si-2Al alloy of Example 2 are subjected to a homogenization heat treatment at 1000°C for 1 hour or 24 hours, both of the cast materials have a more excellent low-cycle fatigue life (the data is not shown).

Industrial Applicability

[0087] By using the Fe-Mn-Si-based cast alloy of the present invention having extremely excellent fatigue properties, it is expected that industrial applications of a cast material are greatly expanded to a structure member for a building and a civil structure, a seismic damper, machine parts, various fasteners and the like as the cast member that can be used not only in the elastic region but also in the plastic region

Claims

1. An Fe-Mn-Si-based cast alloy containing Mn and Si as essential component elements, and one or more of Cr, Ni, Al, and C as an optional component element, said Fe-Mn-Si-based cast alloy consisting of a component composition of:

$$5 \text{ mass\%} \leq \text{Mn} \leq 35 \text{ mass\%},$$

$$1.5 \text{ mass\%} \leq \text{Si} \leq 6.5 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Ni} \leq 15 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Al} \leq 3 \text{ mass\%},$$

and

$$0 \text{ mass\%} \leq \text{C} \leq 0.4 \text{ mass\%},$$

with the balance being Fe and inevitable impurities,

wherein the component composition satisfies the following conditions of Formula (a) and Formula (b),

$$(a): \quad 37 < [\% \text{Mn}] + 0.3[\% \text{Si}] + 0.7[\% \text{Cr}] + 2.4[\% \text{Ni}] + 5.2[\% \text{Al}] + 28[\% \text{C}] < 45,$$

and

$$(b): [\%Ni] + 30[\%C] + 0.5[\%Mn] > 0.75[\%Cr] + 1.125[\%Si] + 2[\%Al],$$

wherein, in the formulae, [%Mn], [%Si], [%Cr], [%Ni], [%Al], and [%C] represent contents (mass%) of Mn, Si, Cr, Ni, Al, and C, respectively.

2. The Fe-Mn-Si-based cast alloy according to claim 1, wherein the component composition is,

$$25 \text{ mass\%} \leq \text{Mn} \leq 35 \text{ mass\%},$$

$$2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Cr} \leq 8 \text{ mass\%},$$

$$0 \text{ mass\%} \leq \text{Al} \leq 3 \text{ mass\%},$$

and

$$0 \text{ mass\%} \leq \text{C} \leq 0.2 \text{ mass\%},$$

with the balance being Fe and inevitable impurities.

3. The Fe-Mn-Si-based cast alloy according to claim 1, wherein the component composition is,

$$10 \text{ mass\%} \leq \text{Mn} \leq 20 \text{ mass\%},$$

$$2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%},$$

$$5 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%},$$

$$5 \text{ mass\%} \leq \text{Ni} \leq 10 \text{ mass\%},$$

and

$$0 \text{ mass\%} \leq \text{C} \leq 0.2 \text{ mass\%},$$

with the balance being Fe and inevitable impurities.

4. The Fe-Mn-Si-based cast alloy according to claim 1, wherein the component composition is,

$$5 \text{ mass\%} \leq \text{Mn} \leq 8 \text{ mass\%},$$

$$2 \text{ mass\%} \leq \text{Si} \leq 6 \text{ mass\%},$$

$9 \text{ mass\%} \leq \text{Cr} \leq 15 \text{ mass\%},$

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$9 \text{ mass\%} \leq \text{Ni} \leq 15 \text{ mass\%},$

and

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$0 \text{ mass\%} \leq \text{C} \leq 0.4 \text{ mass\%},$

with the balance being Fe and inevitable impurities.

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5. A seismic damping device using the Fe-Mn-Si-based cast alloy according to any one of claims 1 to 4.

6. A steel structure or a reinforced concrete structure using the Fe-Mn-Si-based cast alloy according to any one of claims 1 to 4.

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7. A cast material for a seismic damping device using the Fe-Mn-Si-based cast alloy according to any one of claims 1 to 4.

8. Use of the Fe-Mn-Si-based cast alloy according to any one of claims 1 to 4 for a seismic damping device, a steel structure, or a reinforced concrete structure.

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Fig. 1

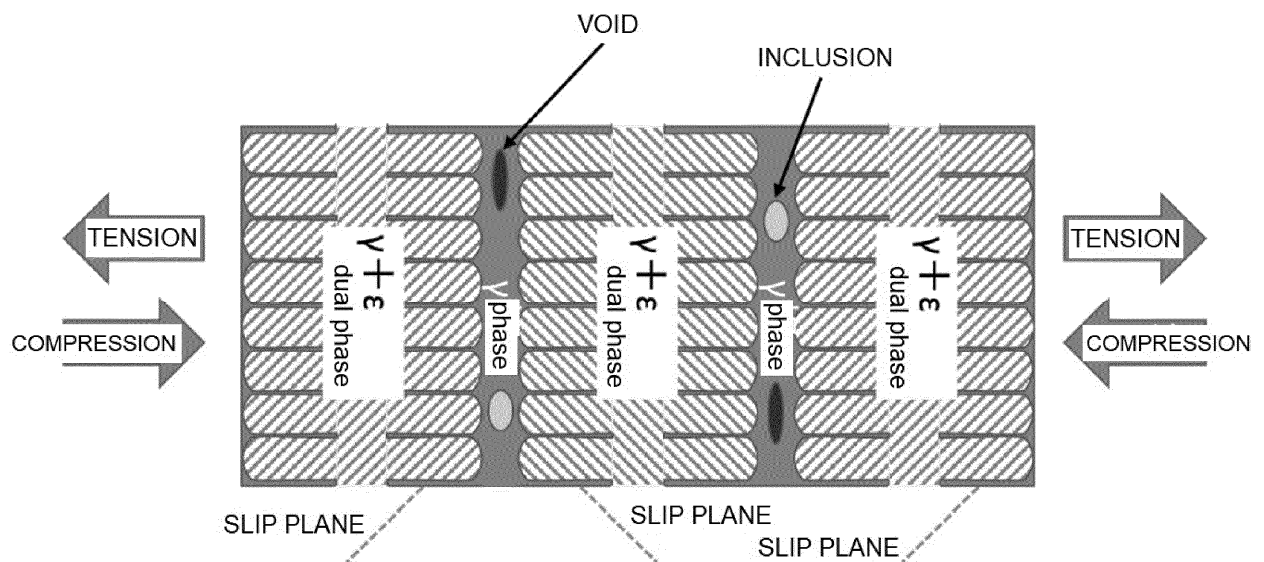


Fig. 2

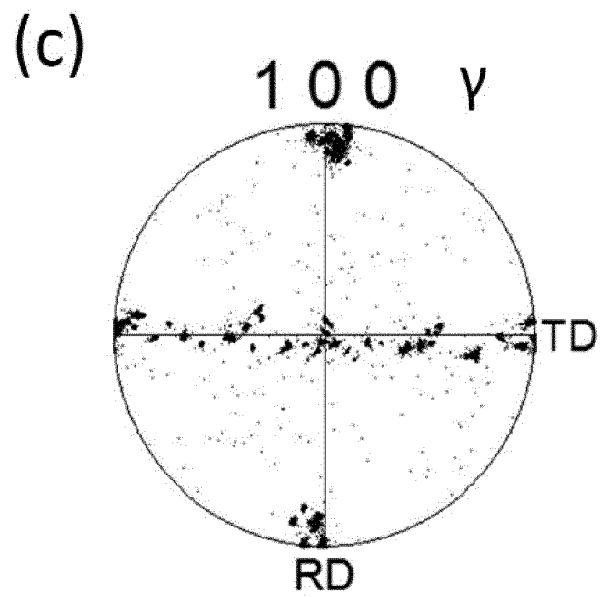
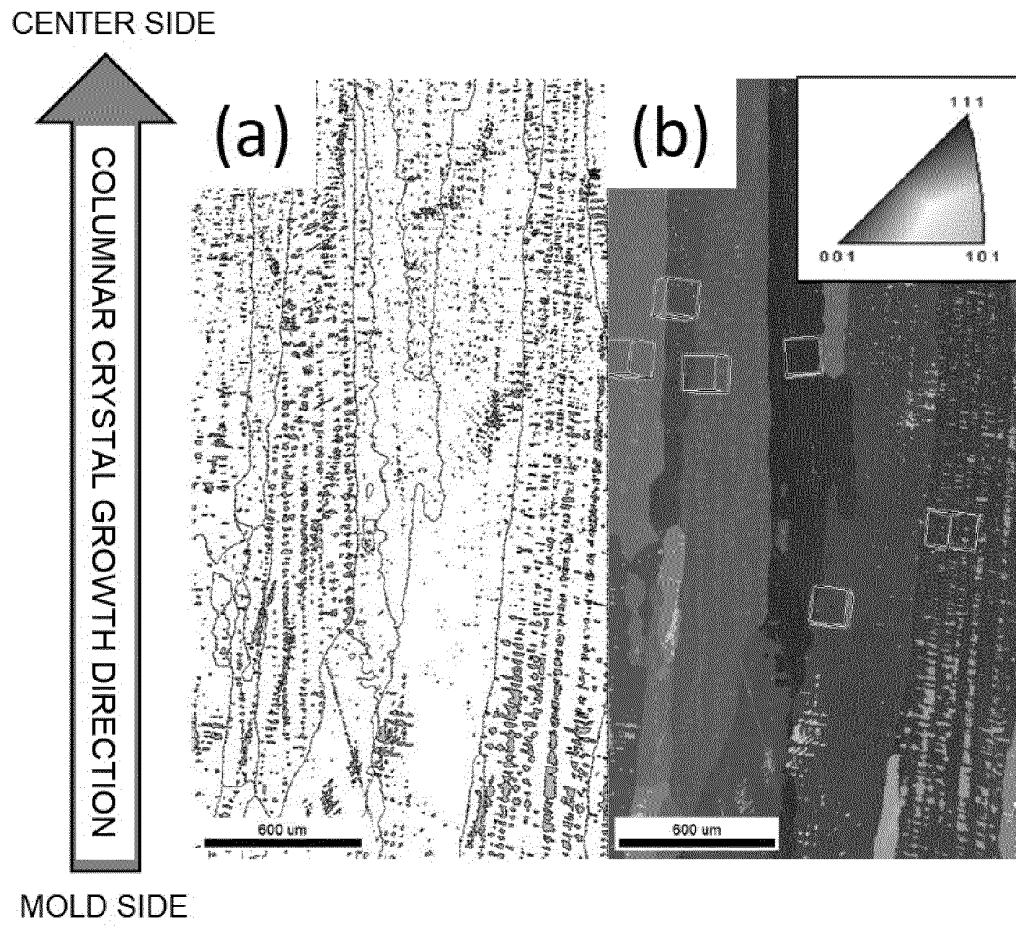


Fig. 3

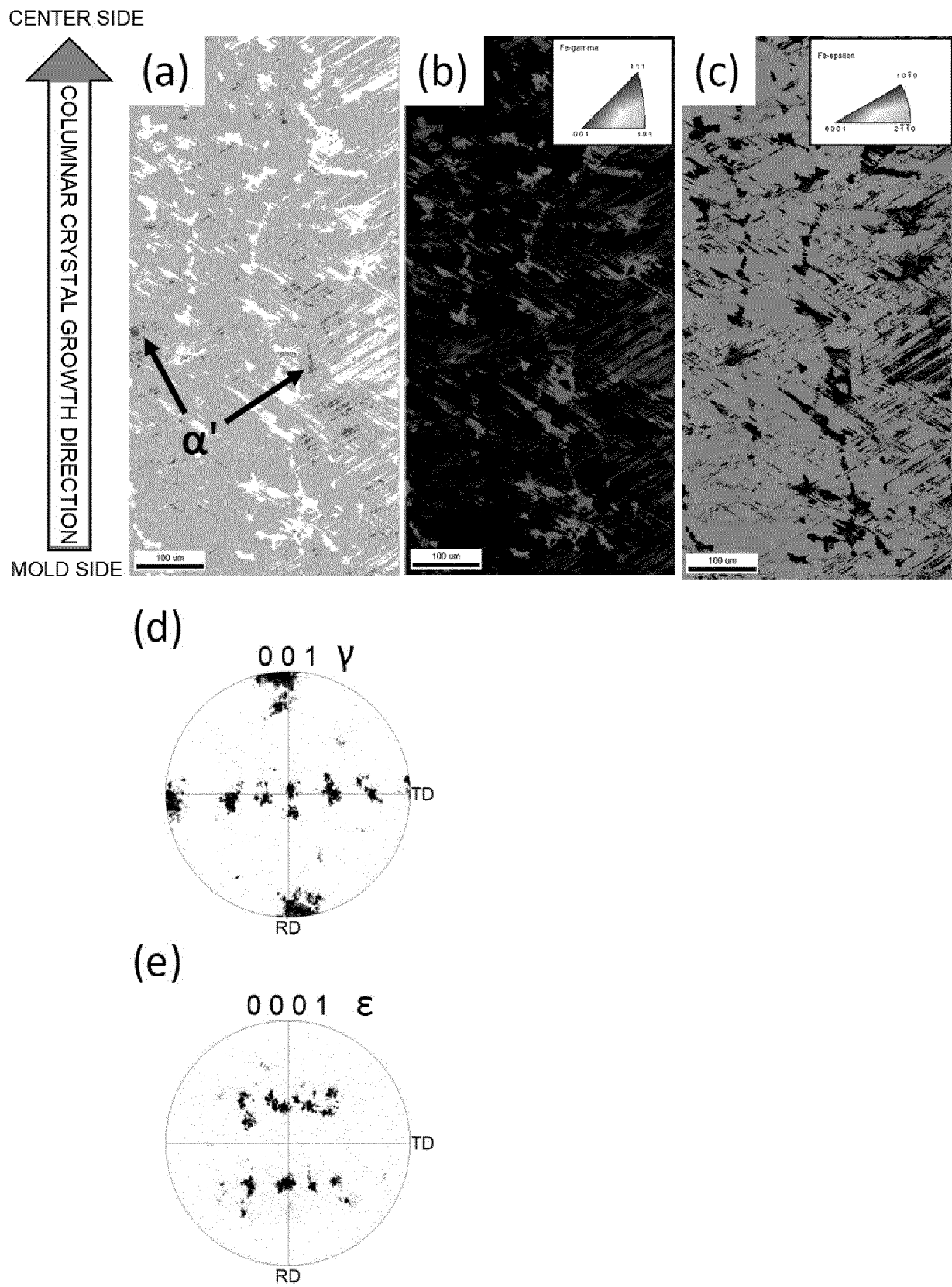


Fig. 4

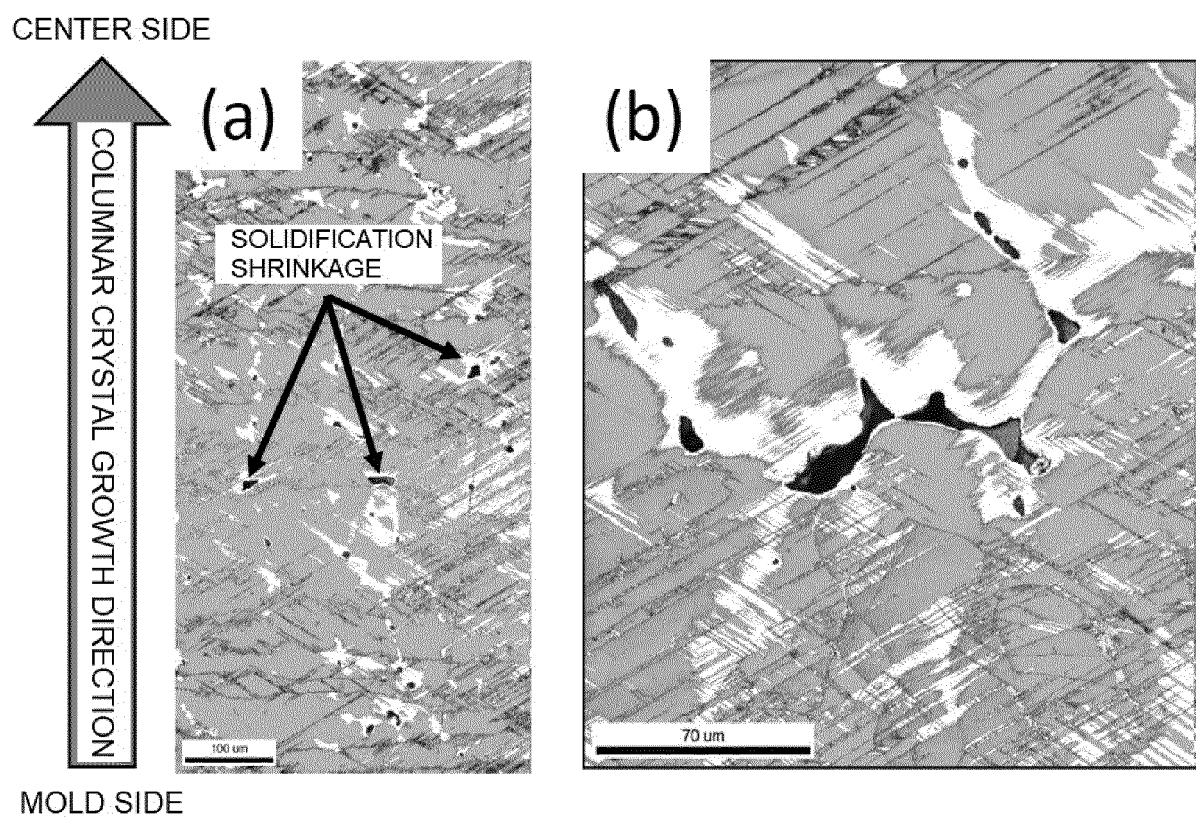


Fig. 5

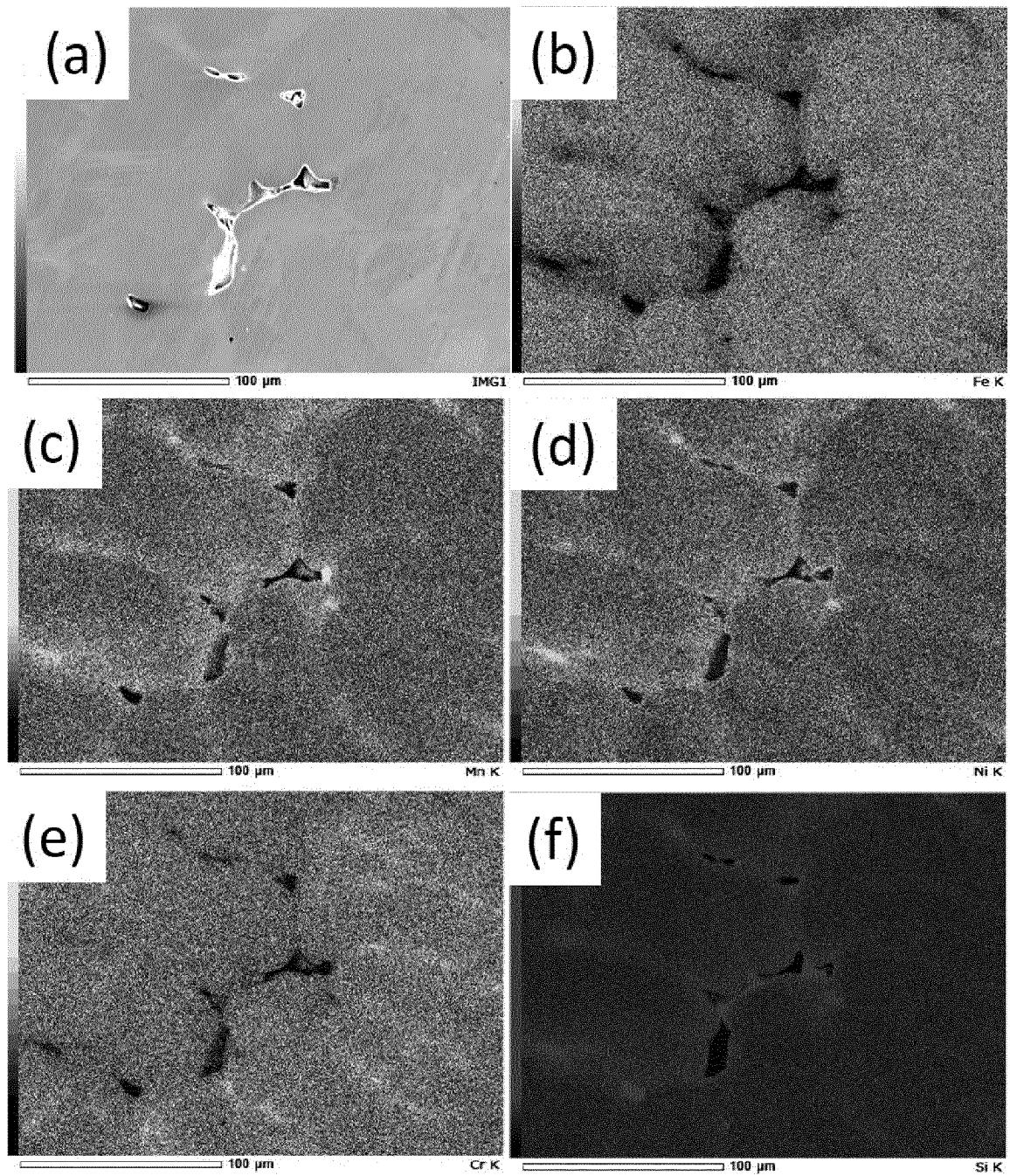
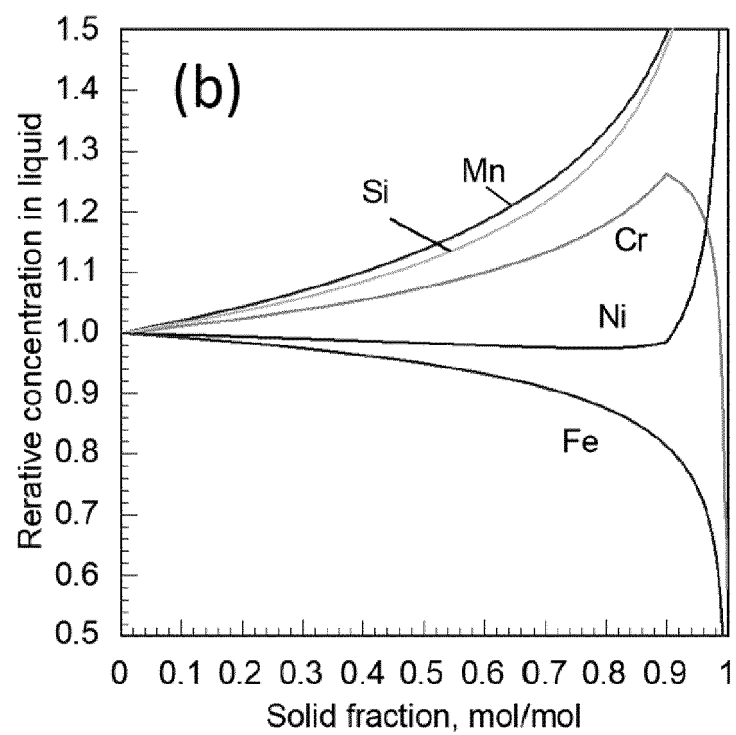
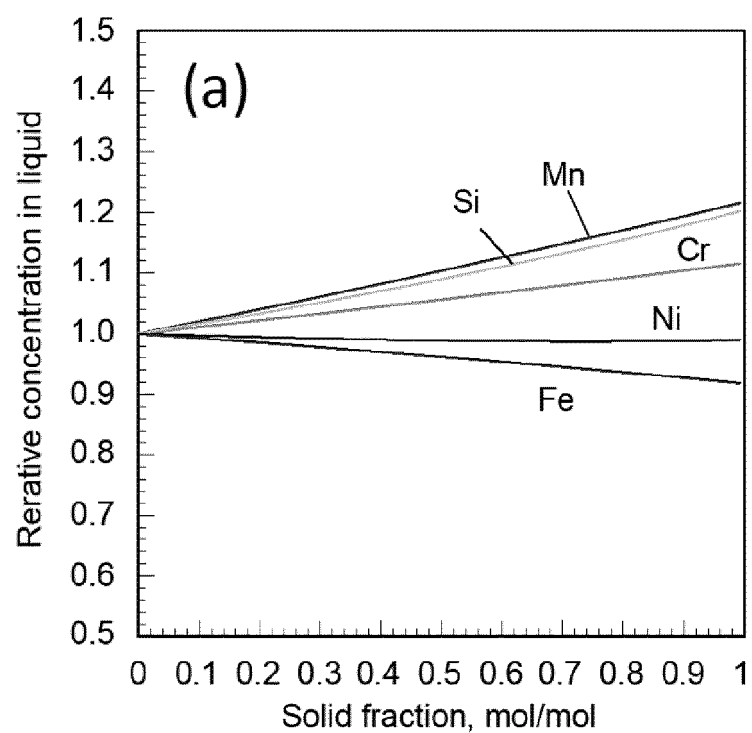


Fig. 6



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2018/014043

A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl. C22C38/00 (2006.01)i, B22D3/00 (2006.01)i, C22C38/58 (2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Int.Cl. C22C38/00, B22D3/00, C22C38/58

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996

Published unexamined utility model applications of Japan 1971-2018

Registered utility model specifications of Japan 1996-2018

Published registered utility model applications of Japan 1994-2018

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	JP 2008-56987 A (INDEPENDENT ADMINISTRATIVE INSTITUTION NATIONAL INSTITUTE FOR MATERIALS SCIENCE) 13 March 2008, paragraphs [0008], [0013], table 1, fig. 1 (Family: none)	1-2, 5-8 3-4
A	JP 5-255813 A (NIPPON STEEL CORP.) 05 October 1993 (Family: none)	1-8
A	JP 2000-501778 A (ULIAKKO, Kari Martti) 15 February 2000 & WO 1997/003215 A1 & EP 846189 A1 & AU 6361396 A & CA 2225679 A1 & RU 2169786 C2	1-8
A	JP 62-112751 A (NIPPON STEEL CORP.) 23 May 1987 (Family: none)	1-8
A	CN 103966529 A (CAO, Shuai) 06 August 2014 (Family: none)	1-8



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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"P" document published prior to the international filing date but later than the priority date claimed

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"X"

document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&"

document member of the same patent family

Date of the actual completion of the international search

21 June 2018 (21.06.2018)

Date of mailing of the international search report

03 July 2018 (03.07.2018)

Name and mailing address of the ISA/
Japan Patent Office
3-4-3, Kasumigaseki, Chiyoda-ku,
Tokyo 100-8915, Japan

Authorized officer

Telephone No.

REFERENCES CITED IN THE DESCRIPTION

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- T. SAWAGUCHI ; T. MARUYAMA ; H. OTSUKA ; A. KUSHIBE ; Y INOUE ; K. TSUZAKI. Design Concept and Applications of Fe-Mn-Si-Based Alloys-from Shape Memory to Seismic Response Control. *Mater. Trans.*, 2016, vol. 57, 283-293 [0020]
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