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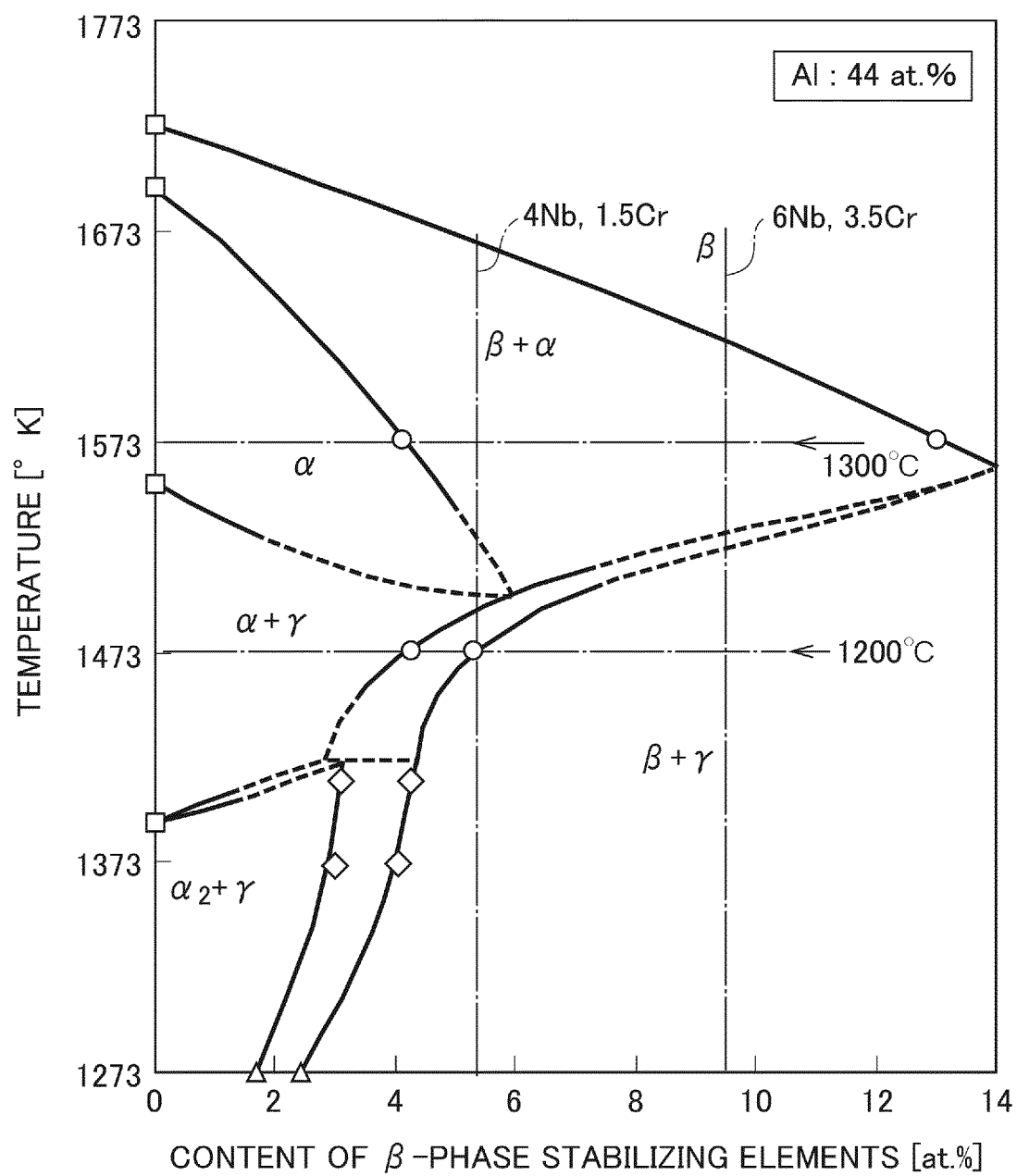
(54) **TITANIUM ALUMINIDE ALLOY MATERIAL FOR HOT FORGING, FORGING METHOD FOR
TITANIUM ALUMINIDE ALLOY MATERIAL, AND FORGED BODY**

(57) A TiAl alloy material for hot forging has a chemical composition including, by atom, Al of 43.0% or greater and 45.0% or less, Nb of 4.0% or greater and 6.0% or less, Cr of 1.5% or greater and 3.5% or less, and Ti and inevitable impurities as a residue. The TiAl alloy material for hot forging may further include boron as necessary. The TiAl alloy material for hot forging is prepared and kept at a temperature within a range of a phase equilib-

rium temperature of any of a β -phase, a $(\beta+\alpha)$ phase, and a $(\beta+\alpha+\gamma)$ phase in a phase diagram of a TiAl alloy so as to be forged in a non-oxidizing atmosphere. The TiAl alloy material for hot forging is subjected to a first heat treatment and a second heat treatment after forging. This improves isothermal forgeability of the TiAl alloy material, so as to execute the hot forging at a lower forging temperature.

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FIG. 1



Description

TECHNICAL FIELD

5 **[0001]** The present disclosure relates to a titanium aluminide alloy material for hot forging, a forging method for a titanium aluminide alloy material, and a forged body.

BACKGROUND ART

10 **[0002]** A titanium aluminide (TiAl) alloy is composed of an intermetallic compound including titanium (Ti) and aluminum (Al). The TiAl alloy has high heat resistance, and has a lighter weight and a higher specific strength than a Ni-based alloy, so as to be used for engine components for aircraft such as turbine blades. The TiAl alloy is, however, a material having low ductility and hard to process, and is thus subjected to isothermal forging as hot forging. JP H05-255781 (referred to below as Patent Literature 1) discloses material characteristics having improved effects due to added elements
15 based on an aluminized titanium alloy. JP 2015-004092 (referred to below as Patent Literature 2) discloses a TiAl alloy including Al in the range of 40.0% to 42.8% by atom, in which the TiAl alloy has a great high-temperature strength and thus can be used as a hot forged material. JP 2009-144247 (referred to below as Patent Literature 3) teaches a method of processing a titanium aluminide alloy including niobium so as to be used for manufacturing structural components.

20 CITATION LIST

PATENT LITERATURE

[0003]

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Patent Literature 1: Japanese Unexamined Patent Application Publication No. H05-255781

Patent Literature 2: Japanese Unexamined Patent Application Publication No. 2015-004092

Patent Literature 3: Japanese Unexamined Patent Application Publication No. 2009-144247

30 SUMMARY OF THE INVENTION

[0004] The processing for the TiAl alloy by the isothermal forging is executed at a low strain rate while keeping a metal die and a TiAl alloy material at substantially the same temperature. Since the forged base material and the metal die are subjected to high temperature, and a forging device including peripheral components are also thermally influenced,
35 the durability of the forging device and the peripheral components tends to be decreased depending on a level of thermal load if the forging temperature is high. In view of this, the demand has grown for executing the forging at a lower temperature so that a general-purpose hot processing method can be applied to the TiAl alloy material. The processability of hot working for the TiAl alloy material thus needs to be improved.

[0005] An object of the present disclosure is to provide a titanium aluminide alloy material for hot forging with processability improved during hot forging, and provide a forging method for the titanium aluminide alloy material so as to
40 obtain a forged body of high quality.

SOLUTION TO PROBLEM

45 **[0006]** An aspect of the present disclosure provides a titanium aluminide alloy material for hot forging having a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, and titanium and an inevitable impurity as a residue.

[0007] Another aspect of the present disclosure provides a titanium aluminide alloy material for hot forging having a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater
50 and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, boron of greater than 0% and 0.25% or less, and titanium and an inevitable impurity as a residue.

[0008] An aspect of the present disclosure provides a hot forging method for a titanium aluminide alloy material including preparing the titanium aluminide alloy material for hot forging described above, and executing hot forging by setting a forging temperature within a range of a phase equilibrium temperature of any of a β -phase, a $(\beta+\alpha)$ phase, and a $(\beta+\alpha+\gamma)$
55 phase in a phase diagram of the titanium aluminide alloy material, and forging the titanium aluminide alloy material while keeping the set forging temperature in a non-oxidizing atmosphere.

[0009] The forging temperature in the hot forging may be set to 1200°C or higher and 1300°C or lower. The hot forging method for the titanium aluminide alloy material preferably further includes a first heat treatment of heating a titanium

aluminide alloy forged body obtained by the hot forging to a temperature of 1240°C or higher and 1290°C or lower, and a second heat treatment of keeping the titanium aluminide alloy forged body through the first heat treatment at a temperature of 900°C or higher and 1100°C or lower for one hour or longer. The temperature of the titanium aluminide alloy forged body after the first heat treatment is preferably temporarily decreased before the second heat treatment step.

[0010] An aspect of the present disclosure provides a titanium aluminide alloy forged body having a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, and titanium and an inevitable impurity as a residue, the titanium aluminide alloy forged body having a metallographic structure including a crystalline grain of a lamellar structure, a crystalline grain of a γ -phase, and a crystalline grain of a β -phase, the metallographic structure having a volume proportion of the γ -phase set to 80% or greater.

[0011] Another aspect of the present disclosure provides a titanium aluminide alloy forged body having a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, boron of greater than 0% and 0.25% or less, and titanium and an inevitable impurity as a residue, the titanium aluminide alloy forged body having a metallographic structure including a grain of a lamellar structure, a grain of a γ -phase, a grain of a β -phase, and a boride grain, the metallographic structure having a volume proportion of the γ -phase set to 80% or greater.

ADVANTAGEOUS EFFECTS

[0012] The present disclosure enables the hot forging for the TiAl alloy material by the isothermal forging in which the forging temperature is set to a lower temperature, so as to use a typical forging technique for metal to process the TiAl alloy material by forging. The present disclosure thus can improve the economic efficiency in terms of processing costs upon manufacture and maintenance costs for a manufacturing device to enhance the manufacturing efficiency of products, so as to contribute to the wide use of the TiAl alloy material.

BRIEF DESCRIPTION OF DRAWINGS

[0013]

[Fig. 1] Fig. 1 is a phase diagram showing phase equilibrium depending on the content of a β -phase stabilizing element on the basis of a composition of Ti-44% by atom of Al.

[Fig. 2] Fig. 2 is a graph showing a relationship between a temperature and a peak stress in a TiAl alloy material for forging.

[Fig. 3] Fig. 3 is a stress-strain diagram obtained by a tensile test for explaining effects of heat treatment after hot forging.

[Fig. 4] Fig. 4 is a graph showing a relationship between a volume proportion of a γ -phase in a metallographic structure and fracture ductility in the TiAl alloy material subjected to hot forging and heat treatment.

[Fig. 5] Fig. 5 is an image of the metallographic structure of the TiAl alloy material subjected to hot forging and heat treatment captured with a scanning electron microscope (SEM).

DESCRIPTION OF EMBODIMENTS

[0014] A metallographic structure of titanium (Ti) shows an α -phase at a normal temperature, and shows a β -phase when heated to an allotropic modification temperature or higher. When aluminum (Al) is added as an alloying element to Ti, Al affects the α -phase (α -Ti) to be stabilized so as to cause a modification temperature of the alloy to increase. When other elements such as molybdenum (Mo), vanadium (V), niobium (Nb), iron (Fe), chromium (Cr), and nickel (Ni) are added to Ti, these elements affect the β -phase (β -Ti) to be stabilized so as to cause the modification temperature of the alloy to decrease.

[0015] A titanium aluminide (TiAl) alloy is an alloy material of TiAl (a γ -phase) or Ti_3Al (an α_2 -phase), for example, which is an intermetallic compound including titanium (Ti) and aluminum (Al). The TiAl alloy is known as a material that can be subjected to hot processing by isothermal forging at a forging speed that barely causes a strain. The field of usage of the TiAl alloy material can be expanded if the processability of hot working for the TiAl alloy material is improved so as to allow the isothermal forging to be executed at a lower temperature, since a thermal load of a forging device and the like is decreased to improve an economic efficiency upon manufacture. The present disclosure provides a TiAl alloy material for hot forging (also referred to below as a TiAl alloy material for forging) with the processability of hot working improved so as to enable the isothermal forging at a lower temperature. The present disclosure also provides a method of manufacturing the TiAl alloy material for hot forging and a forging method for the TiAl alloy material for hot forging.

[0016] According to the present disclosure, a chemical composition of the TiAl alloy is designed to cause a region of

the β -phase in a phase diagram to be expanded toward a low temperature side so as to improve the processability of hot working of the TiAl alloy. To achieve this, the addition of an element that stabilizes the β -phase is effective, since the β -phase has the characteristics of being relatively soft and having high processability of hot working. The titanium aluminide alloy material (the TiAl alloy material) for forging according to the present disclosure is a material solidified from a molten state composed of a TiAl alloy including an element that stabilizes the β -phase, and has a chemical composition designed to lead a metallographic structure to include the β -phase at a target forging temperature. In addition, Al is an α -phase stabilizing element, and the content of Al is set to a low level upon the design of the chemical composition of the TiAl alloy so as to lead the β -phase stabilizing element to function effectively. The TiAl alloy material for forging may include boron (B) in addition to the above constituent components, but the addition of boron is optional. The addition of boron micronizes crystalline grains in the metallographic structure, and enhances ductility of the TiAl alloy material at a high temperature. In view of this, boron can be added to the TiAl alloy material for forging as necessary with a content set to an appropriate range.

[0017] The TiAl alloy material for forging having the chemical composition described above, when heated so as to be led to a isothermal state for executing hot forging, is to include the β -phase in the metallographic structure. Since the β -phase has low high-temperature strength and is soft, the TiAl alloy material including the β -phase in the metallographic structure is easy to subject to forging processing. The β -phase, which can be included in the metallographic structure of a TiAl alloy forged body cooled to a normal temperature through the forging, can be led to characteristic modification by heat treatment. Subjecting the forged body to heat treatment can modify the characteristics of the alloy. In particular, the heat treatment for producing a γ -phase can enhance the high-temperature strength. The forged body cooled through the heat treatment is composed of the TiAl alloy material having the metallographic structure including a lamellar structure (a structure in which an α_2 -phase of about 20% by mass is precipitated in layers in the γ -phase) and the dispersed γ -phase. When the TiAl alloy at this point has the γ -phase with a volume proportion as high as 80% or greater in the metallographic structure, the forged body can exhibit high fracture ductility.

[0018] An embodiment of the present disclosure is described in more detail below with reference to the drawings.

[0019] The TiAl alloy material for hot forging is based on the TiAl alloy mainly including Ti and Al, and includes the β -phase stabilizing element, as described above. The β -phase stabilizing element as used herein is niobium (Nb) and chromium (Cr). In particular, the TiAl alloy material preferably has a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, and titanium and inevitable impurities as residues. The TiAl alloy material may further include boron (B) as necessary. The TiAl alloy material, when including boron, has a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, boron of greater than 0% and 0.25% or less, and titanium and inevitable impurities as residues.

[0020] The content of aluminum (Al) in the TiAl alloy included in the TiAl alloy material for hot forging according to the present disclosure is preferably set to 43% by atom or greater and 45% by atom or less. The forgeability and the tensile strength of the TiAl alloy are improved as the content of Al is lower. However, the decrease in the content of Al leads to a relative increase in the content of Ti, which increases a specific gravity of the TiAl alloy to decrease the specific strength accordingly. In view of this, the lower limit of the content of Al is set to 43% by atom. While a content of Al in an alloy composition provided with a lamellar structure having great high-temperature strength and toughness is set in a range of 47% to 48% by atom, the upper limit of the content of Al in the TiAl alloy material for forging according to the present disclosure is set to 45.0% by atom. This is based on the design intended to have the composition having the advantage of stabilizing the β -phase in view of Al that is the α -phase stabilizing element. This composition leads the metallographic structure of the TiAl alloy material to contain crystalline grains of the lamellar structure and further contain TiAl grains (the γ -phase) and Ti grains (the β -phase) together. If the content of Al is greater than 45.0% by atom, the high-temperature forgeability of the TiAl alloy material is decreased, which requires a high-forging temperature.

[0021] The elements, niobium (Nb) and chromium (Cr), included in the TiAl alloy material are the β -phase stabilizing elements having a function of stabilizing the β -phase in the metallographic structure. The respective β -phase stabilizing elements, when used independently, are effective in decreasing the modification temperature, and can expand the existing region of the β -phase in the phase diagram toward the low temperature side. This improves high-temperature deformability during forging to enhance the processability. For this reason, the present disclosure uses both Nb and Cr. The use of Nb and Cr greatly decreases a peak stress in the TiAl alloy and remarkably improves the forgeability. The element Cr, which causes a eutectoid reaction and shows a phase diagram of β -eutectoid type, exhibits greater β -phase stabilizing performance than Nb. The use of both Nb and Cr can synergistically stabilize the β -phase, so as to reduce the content of Cr to avoid a deterioration in processability because of precipitation of the ω -phase, while effectively enhancing the high-temperature deformability. The hot forging at a lower temperature thus can be executed for the TiAl alloy. The respective added amounts of the elements Nb and Cr are preferably determined so that the total amount is set to 5.5% by atom or greater and 9.5% by atom or less. The decrease in the forging temperature may not be achieved because of an insufficient decrease in the modification temperature if the content in total is less than 5.5% by atom, while the mechanical strength of the TiAl alloy is decreased if the content in total exceeds 9.5% by atom. To synergistically

stabilize the β -phase, a ratio of the content of Nb to the content of Cr (in an atomic ratio) is set in a range of about 1.7 to 2.6, and preferably set to about 2.0. Setting the ratio in this range can stabilize the β -phase appropriately while avoiding embrittlement caused by the eutectoid reaction of Cr.

[0022] The element Nb is effective in improving antioxidation and strength. The content of Nb is preferably set to 4% by atom or greater and 6% by atom or less. Setting the content of Nb in this range can satisfactorily form the β -phase when heated upon the forging. The content of Nb less than 4% by atom cannot sufficiently stabilize the β -phase, or may impede the effect of improving the ductility derived from the combination with Cr, hindering the improvement in the forgeability of the TiAl alloy accordingly. The content of Nb exceeding 6% by atom may cause segregation, and increases the specific gravity of the TiAl alloy.

[0023] The element Cr is the β -phase stabilizing element having a high β -phase stabilizing effect, and improves the forgeability and room-temperature ductility of the TiAlTiAl alloy when added. The content of Cr, which is the element showing the phase diagram of the β -eutectoid type, is preferably set to 1.5% by atom or greater and 3.5% by atom or less. The ductility of the TiAl alloy cannot be improved sufficiently if the content of Cr is less than 1.5% by atom, while the TiAl alloy may be embrittled to decrease the strength if the content of Cr exceeds 3.5% by atom.

[0024] The element, boron (B), has a function of micronizing the crystalline grains produced in the metallographic structure and enhancing the ductility of the TiAl alloy. The addition of B increases the ductility of the TiAl alloy in a temperature range set to 1100°C or higher, and remarkably increases the ductility particularly in a temperature range set to 1200°C or higher. The element B, which has the function of increasing the ductility at a high temperature, is effective in improving the hot forging. The addition of B together with Nb and Cr serving as the β -phase stabilizing elements exhibits the effect of decreasing deformation resistance upon forging, and is thus effective in improving the forgeability.

[0025] The addition of B is optional. The content of B, when added to the TiAl alloy, is preferably set to greater than 0% by atom and 0.25% by atom or less. The crystalline grains produced in the constitution are micronized to have a particle diameter of 200 μm or smaller, or can be further micronized to have the particle diameter reduced to 100 μm or smaller as the content of B is increased. The micronization of the crystalline grains improves the ductility of the TiAl alloy. The content of B is preferably set to 0.25% by atom or less, since a further reduction in the diameter of the crystalline grains cannot be expected or the toughness is decreased if the content exceeds 0.25% by atom. The content of B exceeding 1.0% by atom tends to cause a boride with a size of exceeding 100 μm during the preparation of the TiAl alloy material by casting, which decreases the ductility to decrease the forgeability accordingly. The boride in this case is TiB or TiB₂, for example, and is precipitated into a needle-like shape.

[0026] The addition of B with the content of 0.25% by atom or less as described above can provide the fine structure in which the crystalline grains caused in the metallographic structure of the TiAl alloy material have the particle diameter of 200 μm or smaller. The boride is caused as grains included in such crystalline grains having a particle diameter of 100 μm or smaller. The micronization of the precipitated grains increases the ductility of the TiAl alloy, so as to improve the forgeability. The boride is finely precipitated as grains with the particle diameter of 100 μm or smaller in the crystalline grains in the metallographic structure in the TiAl alloy subjected to the forging and the heat treatment, so as to improve the mechanical strength of the TiAl alloy. The particle diameter of the crystalline grains as used herein refers to an area mean particle diameter converted by the areas of the crystalline grains by image analysis of the cross section of the metallographic structure.

[0027] The element Ti reacts with the air at a high temperature or a gas component in an atmosphere, and can contain impurities such as oxygen or nitrogen in association with surface oxidation or internal diffusion of the impurities. The element Al also can contain oxygen due to the surface oxidation. The TiAl alloy material for forging according to the present disclosure may include such inevitable impurities. For the manufacture of the TiAl alloy material for forging, the prevention of oxidation needs to be taken into consideration in an operating situation such as melting or casting using a raw material at a high temperature, since a deterioration in the properties of the alloy material due to contamination is preferably avoided.

[0028] A method of manufacturing the above TiAl alloy material for forging is described below.

[0029] The method of manufacturing the TiAl alloy material for forging includes a casting step of heating and melting a raw material having a composition entirely corresponding to the chemical composition of the TiAl alloy material as described above to cast the TiAl alloy material. The raw material may be in a state of any of powder, a metal piece, and a metal ingot, or may be in a combined state of two or more thereof. The powder state, the metal piece, and the metal ingot each may be either simple metal of the components included in the TiAl alloy material or an alloy of the plural constituent components. The raw material may be chosen as appropriate from a mixture of the simple metals, a mixture of the simple metal and the alloy, the alloy itself, and a mixture of the alloys. The raw material can be prepared with the combination of the respective components so as to entirely have the chemical composition of the TiAl alloy material as described above. Alternatively, a raw material preliminarily prepared to have the chemical composition as described above may be obtained and used. When boron is used as a simple element for preparing the raw material, the content of boron is preferably set to 0.2% by atom or greater and 1.0% by atom or less, and more preferably set to 0.5% by

atom or greater and 1% by atom or less, in view of a loss and an error in measurement during the preparation.

[0030] The casting step includes melting processing of heating and melting the raw material prepared as described above, and molding processing of cooling the melted raw material to cast the material into an ingot. These processing steps can provide the material solidified from a molten state of the TiAl alloy having the chemical composition as described above to be used as the TiAl alloy material for forging. The casting is preferably executed by use of a melting technique and a casting technique as appropriate typically used for casting metallic materials. Examples of techniques include a vacuum arc melting-centrifugal casting method, a melting-casting method (a Levicast method), and a precision casting technique in which a crucible covered with a face coat and centrifugal casting are combined together. A device used in the casting step may be any device that can prevent an entry of impurities and a reaction such as oxidation, and may be a casting device such as a vacuum induction furnace, for example.

[0031] The material solidified from a molten state obtained by the casting may be subjected to hot isostatic pressing (HIP) treatment. The HIP treatment can avoid internal defects such as casting defects. The HIP treatment may use a HIP device typically used for processing metallic materials.

[0032] The method of manufacturing the TiAl alloy material for forging may further include surface processing of removing a casted surface (a surface layer) of the material solidified from a molten state of the TiAl alloy obtained by the casting step. This processing can avoid a decrease in the processability caused by an oxidation film on the surface, so as to provide the TiAl alloy material for forging having a fine surface condition. The surface processing may be executed by cutting or grinding, for example. When the TiAl alloy material externally manufactured is obtained and forged, the surface processing is preferably executed immediately before the forging step at the preparation stage in the hot forging method.

[0033] The TiAl alloy material for forging can be processed into a TiAl alloy forged body having an intended shape in accordance with the following hot forging method. In particular, the hot forging method for the TiAl alloy material includes a step of preparing the TiAl alloy material for hot forging having the chemical composition as described above, and a hot forging step of heating the TiAl alloy material for hot forging to a forging temperature in a non-oxidizing atmosphere, and executing the forging while keeping the forging temperature constant. The surface processing described above may be included in the step of preparing the TiAl alloy material for hot forging.

[0034] The forging temperature is set within a range of a phase equilibrium temperature in which the β -phase can be present in the phase diagram of the TiAl alloy, namely, in the range of the phase equilibrium temperature of any of the β -phase, the $(\beta+\alpha)$ phase, and the $(\beta+\alpha+\gamma)$ phase. In particular, the forging temperature is preferably set as follows with reference to the phase diagram of the TiAl alloy.

[0035] Fig. 1 is a phase diagram in which a relationship is examined between the content of the β -phase stabilizing elements (the sum [% by atom] of the contents of Nb and Cr) and the phase equilibrium state of the TiAl alloy on the basis of the composition of Ti-44% by atom of Al. When the alloy including the β -phase stabilizing elements with the content in the range of 5.5% to 9.5% by atom is heated so that the temperature is increased from the room temperature, the phase condition of the alloy is shifted to the β -phase through the $(\beta+\gamma)$ phase, the $(\beta+\alpha+\gamma)$ phase, and the $(\beta+\alpha)$ phase. When the content of the β -phase stabilizing elements is 6% by atom or less, the phase condition can be shifted further through the $(\alpha+\gamma)$ phase and the α -phase between the $(\beta+\alpha+\gamma)$ phase and the $(\beta+\alpha)$ phase, while the region of the α -phase itself is small. It is thus easy to avoid coarseness of the α -phase particles during the temperature change. It is apparent from the phase diagram shown in Fig. 1 that the β -phase is present in the alloy to improve the forgeability at a temperature of 1200°C (1473°K) or higher, and preferably at a temperature of 1250°C (1523°K) or higher. The forging temperature thus can be set to 1200°C or higher, and preferably set to 1250°C or higher. While the upper limit of the forging temperature can be set in the range in which the β -phase can be present, the TiAl alloy material having the chemical composition as described above can be forged appropriately at a temperature of 1300°C (1573°K) or lower. This temperature thus can be set as the upper limit in view of the durability for the forging device. The forging temperature can be set to about 1200°C or higher and about 1300°C or lower in accordance with the phase diagram, while keeping the TiAl alloy material at the temperature in this range to execute the isothermal forging.

[0036] The hot forging step is preferably executed in the non-oxidizing atmosphere to avoid oxidation. The non-oxidizing atmosphere may be an inert gas atmosphere such as argon gas, for example. The forging method may be chosen as appropriate from typical forging methods for metallic materials such as free forging, die forging, roll forging, and extrusion forging, and a forging device to be used may be chosen as appropriate in accordance with the forging method to be applied. The TiAl alloy material for hot forging according to the present disclosure can also be used for hot pressing or hot rolling. In the case of the die forging, the molding temperature is preferably set to about 700°C or higher in view of keeping the temperature of the TiAl alloy material. The processing by the hot forging can be executed appropriately at a strain rate of about 0.1 per second or higher. Since the peak stress in the TiAl alloy material is small and the deformation resistance is low, the forging processing can be executed appropriately without causing forging breakage at a strain rate in a range of about 1 to 10 per second.

[0037] The TiAl alloy material heated to the forging temperature improves in the high-temperature ductility since the β -phase is present in the metallographic structure, so as to allow plastic deformation by the forging to advance smoothly.

The forging decreases the casting defects in the TiAl alloy material, and splits the metallographic structure into the fine crystalline grains. The metallographic structure can be micronized finely as the processing degree during forging is larger. The forging processing is available in which an effective strain is in a range of about 0.5 to 1.

[0038] The titanium aluminide alloy forged body (the TiAl alloy forged body) obtained by the hot forging step is temporarily cooled. The cooling process may be made either in the forging device or by external air cooling. Since the chemical composition of the TiAl alloy material for hot forging is designed to lead the β -phase to be stabilized, the coarseness of the crystalline grains due to the growth of the α -phase in the metallographic structure is avoided by the cooling process after the forging.

[0039] While the β -phase can remain in the TiAl alloy forged body, the metallographic structure can be reorganized when subjected to heat treatment so as to have high-temperature strength necessary for products. The method of forging the TiAl alloy material thus preferably further includes the heat treatment made for the forged body obtained by the hot forging step. The heat treatment is preferably executed in the non-oxidizing atmosphere to avoid oxidation. Examples of the non-oxidizing atmosphere include an inert gas atmosphere such as argon gas, a vacuum atmosphere, and a reducing atmosphere such as hydrogen gas.

[0040] The heat treatment made for the TiAl alloy forged body preferably includes a first heat treatment step and a second heat treatment step. The first heat treatment step heats the TiAl alloy forged body obtained by the forging step to a temperature of 1240°C or higher and 1290°C or lower. The heating temperature is within the phase equilibrium temperature range of either the ($\beta+\alpha$) phase or the ($\beta+\alpha+\gamma$) phase in the phase diagram, and the TiAl alloy composing the forged body is led to be in the state in which the α -phase can be present.

[0041] The first heat treatment step only needs to be executed such that the internal temperature of the TiAl alloy forged body reaches about the temperature range described above. The treatment time in the first heat treatment step can be basically set to 15 minutes or longer, and practically set in a range of about one to five hours.

[0042] The forged body through the first heat treatment is preferably cooled before the second heat treatment so as to temporarily lower the temperature. The second heat treatment step leads the TiAl alloy forged body reaching a normal temperature through the first heat treatment step to be kept at a temperature of 900°C or higher and 1100°C or lower for one hour or longer. The heating temperature is preferably kept for one hour or longer and five hours or shorter. The TiAl alloy forged body through the second heating treatment is then cooled to around a room temperature.

[0043] The first heat treatment step relaxes a stress strain of the crystalline grains due to the forging to cause new crystalline grains without strain instead of the grains deformed by the strain. The α -phase generated in the TiAl alloy is then dispersed and precipitated as fine crystalline grains. The first heat treatment executed thus corresponds to a recrystallizing treatment. The second heat treatment step has an effect as an aging treatment that relaxes a strain in the crystalline grain boundary. In the second heat treatment step, the crystalline grains of the lamellar structure composed of the α_2 -phase and the γ -phase are generated from the α -phase. The second heat treatment step leads the TiAl alloy composing the forged body to have the metallographic structure having the crystalline grains of the lamellar structure, the crystalline grains of the γ -phase, and the crystalline grains of the β -phase (refer to Fig. 5 described below). The β -phase stabilizing elements are mixed to form a solid solution in Ti.

[0044] When the TiAl alloy material includes boron, the fine boride is precipitated into a needle shape in the crystalline grains when the TiAl alloy forged body is subjected to the heat treatment. The TiAl alloy composing the forged body thus has the metallographic structure including the fine boride grains having a particle size of about 0.1 μm or smaller, in addition to the crystalline grains of the lamellar structure and the crystalline grains of the γ -phase and the β -phase. The boride grains are composed of TiB or TiB₂, for example.

[0045] The TiAl alloy for forging is designed to have the chemical composition easy to avoid the coarseness of the crystalline grains during the temperature change, so as to improve the high-temperature processability due to the improvement in the ductility. The TiAl alloy thus can be subjected to the hot forging at a greater strain rate while avoiding forging breakage. While conventional isothermal forging for a TiAl alloy executes hot forging processing at a low strain rate in a range of about 5×10^{-5} to 5×10^{-1} per second, the TiAl alloy for forging according to the present disclosure can reduce the peak stress to a lower level. The forging thus can be executed at a strain rate of 1 per second or higher, or even the higher forging can be executed at a strain rate of 10 per second or higher, so as to improve the productivity of components such as turbine blades. The TiAl alloy forged body through the forging processing can also improve in the ductility and have the durability due to the heat treatment. The TiAl alloy material for forging thus can be effectively used as a forging material for manufacturing engine components for aircraft such as turbine blades by the hot forging.

EXAMPLE 1

<Preparation of TiAl Alloy Material for Forging>

[0046] A TiAl alloy raw material was prepared for each of samples 1 to 8 having a chemical composition (by atom) listed below and melted in a high-frequency vacuum melting furnace to be poured to a die, and was then cooled to a

normal temperature and casted, so as to prepare a sample of a TiAl alloy material for forging. The indication of inevitable impurities in each example is omitted below since the content thereof is quite small.

[0047]

Sample 1: Ti-44.4 of Al-4.1 of Nb-5.2 of V
 Sample 2: Ti-43.7 of Al-4.1 of Nb-5.1 of V-0.1 of C
 Sample 3: Ti-43.9 of Al-4.1 of Nb-5.1 of V-0.2 of C
 Sample 4: Ti-44.7 of Al-3.7 of Nb-3.5 of V
 Sample 5: Ti-44.6 of Al-3.6 of Nb-3.8 of V-0.07 of B
 Sample 6: Ti-45.9 of Al-5.3 of Nb-4.0 of V-0.15 of B
 Sample 7: Ti-43.6 of Al-5.2 of Nb-2.6 of Cr-0.15 of B
 Sample 8: Ti-43.0 of Al-4.0 of Nb-1.0 of Mo-0.15 of B

<Evaluation of Forgeability by Measurement of Peak Stress>

[0048] The samples of the TiAl alloy material for forging (samples 1 to 8) conforming to a predetermined shape of the die were prepared as described above as test pieces for a compression test. The following compression test was executed for the samples by use of the respective test pieces.

[0049] The temperature was kept constant in a range of 1150°C to 1300°C, the respective test pieces each held between two parallel plate surfaces of a test device were applied with a load to be subjected to the compression test at a strain rate of each of 0.01 per second, 0.1 per second, 1 per second, and 10 per second so as to obtain a true stress-strain curve up to true strain of 1.2. The maximum stress in this curve was acquired as a peak stress. The strain rate as used herein was a strain rate of true strain. The temperature was changed within the range as described above to repeat the compression test so as to obtain a relationship between the temperature and the peak stress. Fig. 2 shows the results.

[0050] Evaluation revealed as shown in Fig. 2 that the peak stress is remarkably low in the TiAl alloy material of sample 7, and the forgeability in sample 7 at a low temperature is much higher than the other samples. The peak stress in sample 7 corresponds to a value in the other samples at a temperature increased by about 50°C or more according to the results shown in Fig. 2. It can be considered that sample 7 can be forged at a lower temperature decreased by about 50°C or more than the other samples, and the forging temperature can be set in the range of 1200°C to 1300°C. The improvement in the forgeability described above is presumed to be derived from the composition in which both Nb and Cr are added.

EXAMPLE 2

<Preparation of TiAl Alloy Material Sample for Forging: Sample 9>

[0051] A sample of a TiAl alloy material for forging (sample 9) having a chemical composition of Ti-44.0 of Al-5.0 of Nb-2.5 of Cr was prepared by the same preparation method as Example 1. The sample of the TiAl alloy for forging was molded into a predetermined shape by use of the die in the sample preparation.

<Hot Forging for TiAl Alloy Material>

[0052] The sample of the TiAl alloy material for forging was heated in an inert atmosphere of argon gas to be kept at a temperature in a range of 1250°C to 1275°C, and was then subjected to die press forging at a strain rate of 1 per second, so as to be processed into a test piece having a predetermined size (ϕ 8 mm $\times$ 12 mm).

<Heat Treatment after Forging and Evaluation>

[0053] The test piece forged was used to execute the first heat treatment step and the second heat treatment step in accordance with any of the following conditions C1 to C7. The test piece was temporarily cooled to a normal temperature by furnace cooling after the respective heat treatment steps. The heat-treated test piece was then subjected to a tensile test with a greeble testing device so as to measure elongation at the normal temperature. In particular, a predetermined tensile force was applied to both ends of the test piece and was gradually increased until the test piece was broken in the inert atmosphere of argon gas as a test atmosphere. A stress-strain diagram was then formed to measure the elongation. Fig. 3 is the stress-strain diagram of the test piece subjected to the respective heat treatments under the condition C6 or C7.

	First Heat Treatment	Second Heat Treatment
Condition C1	1250°C × 1 h	900°C × 1 h
Condition C2	1250°C × 1 h	900°C × 5 h
Condition C3	1250°C × 1 h	950°C × 1 h
Condition C4	1250°C × 1 h	950°C × 5 h
Condition C5	1280°C × 1 h	1100°C × 1 h
Condition C6	1300°C × 1 h	none
Condition C7	1250°C × 1 h	1000°C × 1 h

[0054] The value of the elongation of the test piece after the heat treatments was 1.1% (the condition C1), 1.2% (the condition C2), 1.2% (the condition C3), 1.0% (the condition C4), 1.8% (the condition C5), 0.1% (the condition C6), and 1.4% (the condition C7). Evaluation revealed that the fracture ductility (the value of the elongation) of the TiAl alloy material differs depending on the heat treatment conditions.

[0055] It is clear from the result under the condition C6 that the improvement in the elongation is small only when subjected to the first heat treatment. The execution of both the first heat treatment and the second heat treatment is thus remarkably effective for the improvement in the elongation. In addition, the first heat treatment is effectively operated at the temperature of 1250°C or higher, and the temperature setting for the first heat treatment is appropriate in the range of 1250°C to 1280°C. The second heat treatment is effectively operated at the temperature of 900°C or higher, and the temperature setting for the second heat treatment is appropriate in the range of 900°C to 1100°C.

EXAMPLE 3

[0056] The sample of the TiAl alloy material in sample 9 subjected to the hot forging in Example 2 was used to form a test piece subjected to heat treatment under the conditions variously changed. Each of the test pieces obtained was subjected to the tensile test in the same manner as Example 2 to measure the value of the elongation [%].

[0057] The metallographic structure of the TiAl alloy was observed with a scanning electron microscope (SEM) for each of the test pieces. An area proportion of the γ -phase (TiAl) in the captured image of the metallographic structure was calculated by image processing by use of contrast information in the image. The value obtained was presumed to be a volume proportion [%] of the γ -phase in the metallographic structure, so as to form a graph showing a relationship between the volume proportion of the γ -phase and the value of the elongation obtained as described above. Fig. 4 is the graph thus obtained.

<Sample 10>

[0058] A sample of a TiAl alloy material for forging (sample 10) having a chemical composition of Ti-44.0 of Al-4.2 of Nb-3.3 of Cr was prepared through the preparation process as in the case of Example 2. The sample of the TiAl alloy material was subjected to the same hot forging as Example 2 to be processed into a test piece having a predetermined size, and was further subjected to the heat treatment under the condition C3. The test piece thus obtained was measured to obtain the elongation by the tensile test and obtain the volume proportion of the γ -phase in accordance with the captured image of the metallographic structure in the same manner as described above.

<Evaluation of Influence by Heat Treatment Executed for Forged Body of TiAl Alloy Material>

[0059] The volume proportion of the γ -phase includes the volume proportion of the γ -phase crystalline grains and the volume proportion of the γ -phase composing the lamellar structure. According to the graph in Fig. 4, it is apparent that the volume proportion of the γ -phase in the metallographic structure has a correlation with the fracture ductility (the value of the elongation) of the alloy material, and that the ductility of the TiAl alloy is improved as the proportion of the γ -phase is increased. Fig. 4 indicates that the test piece shows the elongation of 1% or greater when the volume proportion of the γ -phase in the metallographic structure is about 80% or greater. Evaluation revealed that subjecting the test piece to the heat treatment to lead the volume proportion of the γ -phase to about 80% or greater can provide the forged body of the TiAl alloy material exhibiting the favorable ductility.

[0060] Fig. 4 is the graph showing the measurement value indicated as sample 9 that is the result obtained for the test piece in which the forged body was subjected to the heat treatment under the condition C3 or C6, and also showing the measurement result obtained for sample 10 as described above. The samples 9 and 10 commonly subjected to the heat treatment under the same condition C3 differ from each other only in the ratio Nb/Cr in the β -phase stabilizing

elements, so as to understand the influence derived from the ratio Nb/Cr by the comparison therebetween. The higher ratio Nb/Cr tends to provide the ductility more to the alloy material, and the ductility is higher when the ratio of the Nb content to the Cr content (by atom) is about 1.7 or greater. Namely, it can be presumed that the embrittlement caused by the eutectoid reaction of Cr is avoided so as to exhibit the favorable ductility when the ratio of the Nb content to the Cr content is about 1.7 or greater.

[0061] Fig. 5 is an image of the metallographic structure of the test piece subjected to the heat treatment under the condition C5 after the forging executed for the TiAl alloy material of sample 9 captured with a scanning electron microscope (SEM). As shown in Fig. 5, the metallographic structure of the TiAl alloy forged body has the crystalline grains of the lamellar structure (α_2/γ), the crystalline grains of the β -phase (Ti), and the crystalline grains of the γ -phase (TiAl). These crystalline grains are caused from the crystalline grains finely broken by the forging. The lamellar structure has the high-temperature strength and has the ductility and the toughness to some extent, and the γ -phase has the greater high-temperature strength. The ductility at a high temperature is ensured due to the fine grains of the remaining β -phase. The constitution structure, which includes the grains of the lamellar structure, the grains of the β -phase, and the grains of the γ -phase finely mixed and dispersed together, has the improved high-temperature strength and also has high durability. The improvement in the processability of the TiAl alloy material during the hot forging and the retention of the high-temperature strength of the TiAl alloy material after the forging both can be achieved simultaneously with the same chemical composition.

INDUSTRIAL APPLICABILITY

[0062] The present disclosure can provide the TiAl alloy forged body having high-temperature strength and high ductility at a normal temperature while contributing to decreasing the temperature upon hot forging for the TiAl alloy material, so as to be applied to the manufacture of components such as engines for aircraft and rotor blades and discs of gas turbines for power generation to contribute to providing products of high quality. The present disclosure can also enhance the economic efficiency so as to contribute to the expansion of the applicable range of hot forging for the TiAl alloy material.

Claims

1. A titanium aluminide alloy material for hot forging having a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, and titanium and an inevitable impurity as a residue.
2. A titanium aluminide alloy material for hot forging having a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, boron of greater than 0% and 0.25% or less, and titanium and an inevitable impurity as a residue.
3. A hot forging method for a titanium aluminide alloy material, the method comprising:
 - preparing the titanium aluminide alloy material for hot forging according to claim 1 or 2; and
 - executing hot forging by setting a forging temperature within a range of a phase equilibrium temperature of any of a β -phase, a $(\beta+\alpha)$ phase, and a $(\beta+\alpha+\gamma)$ phase in a phase diagram of the titanium aluminide alloy material, and forging the titanium aluminide alloy material while keeping the set forging temperature in a non-oxidizing atmosphere.
4. The hot forging method for the titanium aluminide alloy material according to claim 3, wherein the forging temperature in the hot forging is set to 1200°C or higher and 1300°C or lower.
5. The hot forging method for the titanium aluminide alloy material according to claim 3 or 4, further comprising:
 - executing a first heat treatment of heating a titanium aluminide alloy forged body obtained by the hot forging to a temperature of 1240°C or higher and 1290°C or lower; and
 - executing a second heat treatment of keeping the titanium aluminide alloy forged body through the first heat treatment at a temperature of 900°C or higher and 1100°C or lower for one hour or longer.
6. The hot forging method for the titanium aluminide alloy material according to claim 5, wherein the temperature of the titanium aluminide alloy forged body after the first heat treatment is temporarily decreased before the second

heat treatment step.

7. A titanium aluminide alloy forged body having a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, and titanium and an inevitable impurity as a residue,
the titanium aluminide alloy forged body having a metallographic structure including a crystalline grain of a lamellar structure, a crystalline grain of a γ -phase, and a crystalline grain of a β -phase, the metallographic structure having a volume proportion of the γ -phase set to 80% or greater.
8. A titanium aluminide alloy forged body having a chemical composition including, by atom, aluminum of 43.0% or greater and 45.0% or less, niobium of 4.0% or greater and 6.0% or less, chromium of 1.5% or greater and 3.5% or less, boron of greater than 0% and 0.25% or less, and titanium and an inevitable impurity as a residue,
the titanium aluminide alloy forged body having a metallographic structure including a crystalline grain of a lamellar structure, a crystalline grain of a γ -phase, a crystalline grain of a β -phase, and a boride grain, the metallographic structure having a volume proportion of the γ -phase set to 80% or greater.

FIG. 1

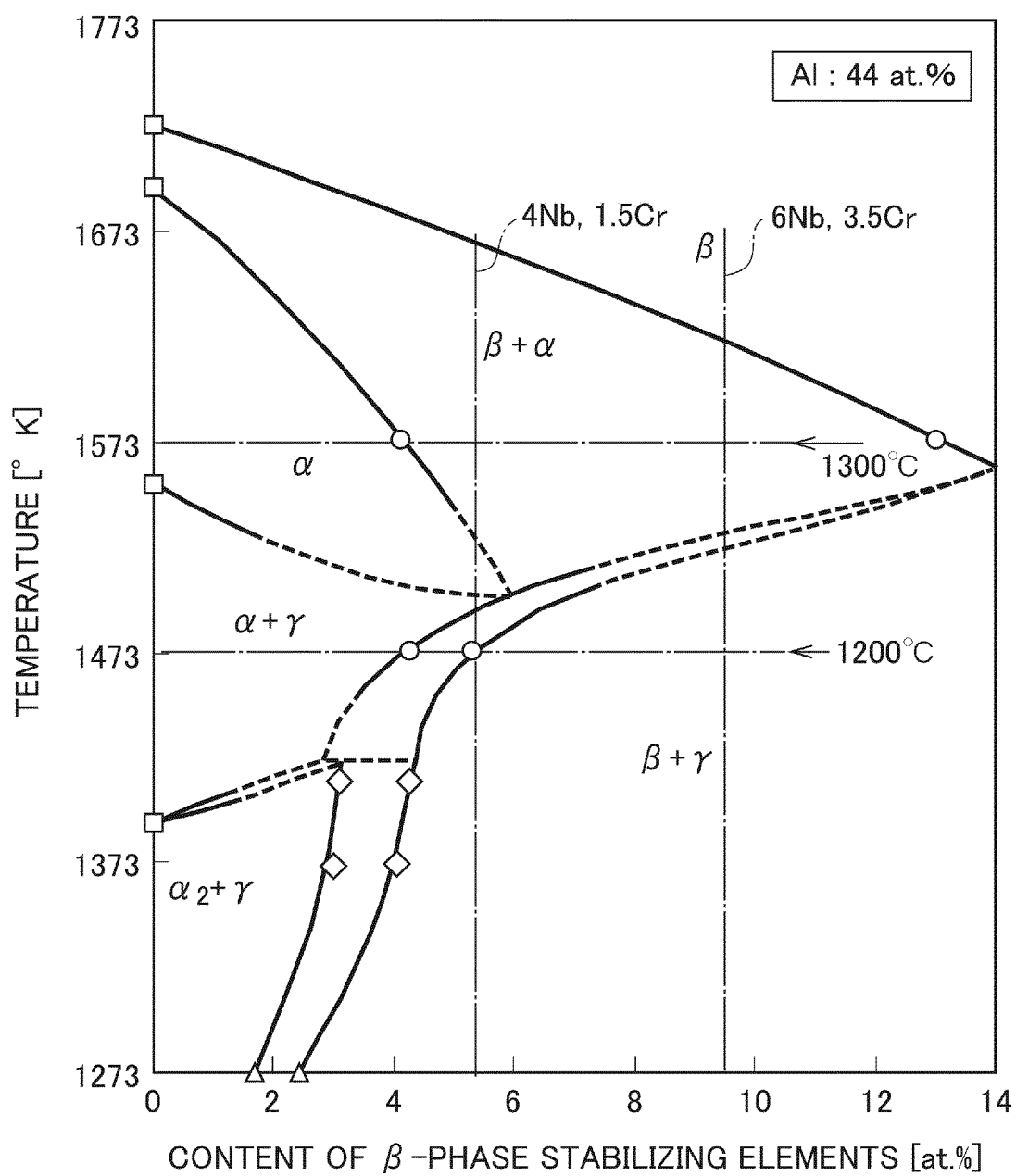


FIG. 2

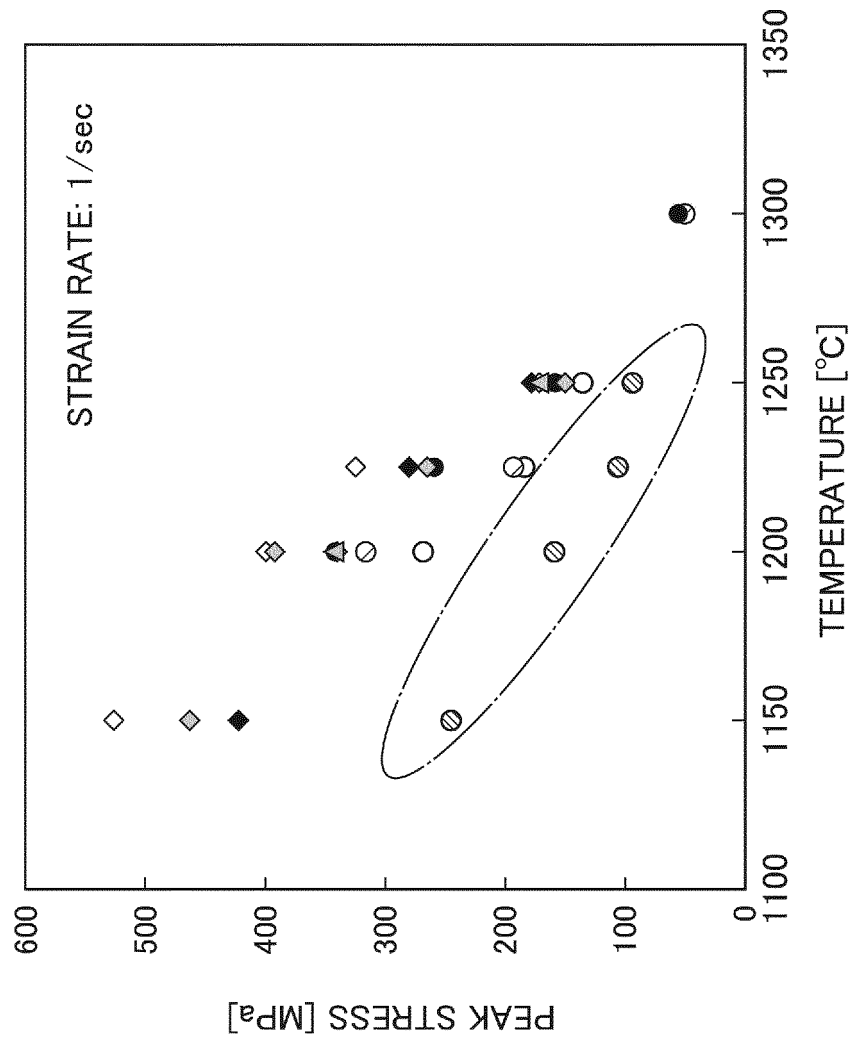


FIG. 3

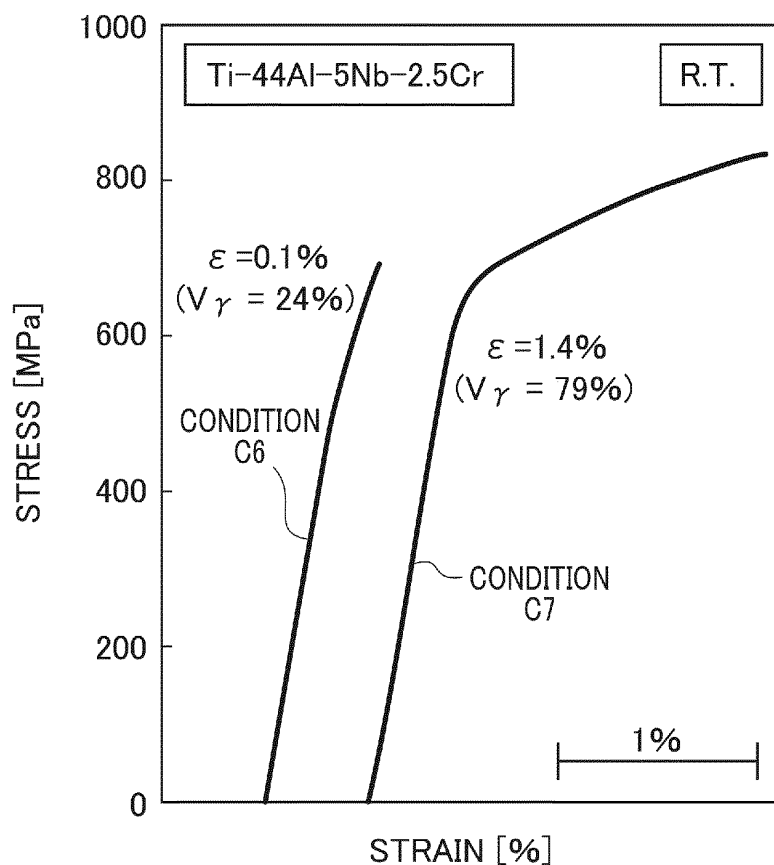


FIG. 4

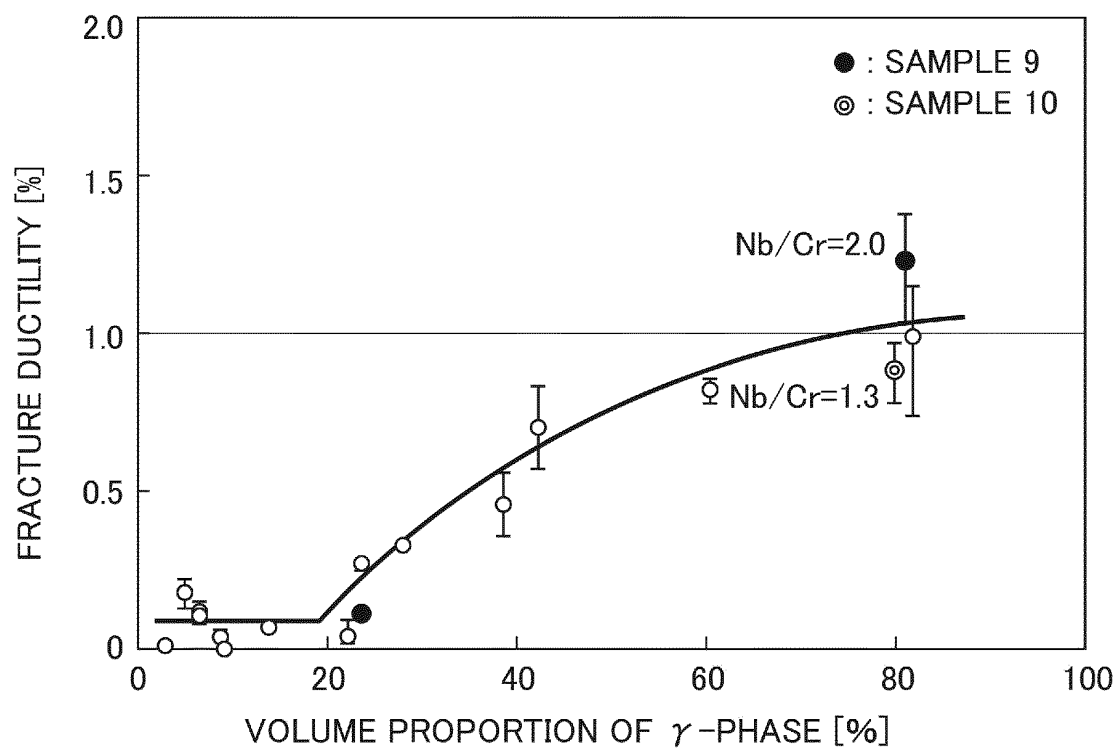
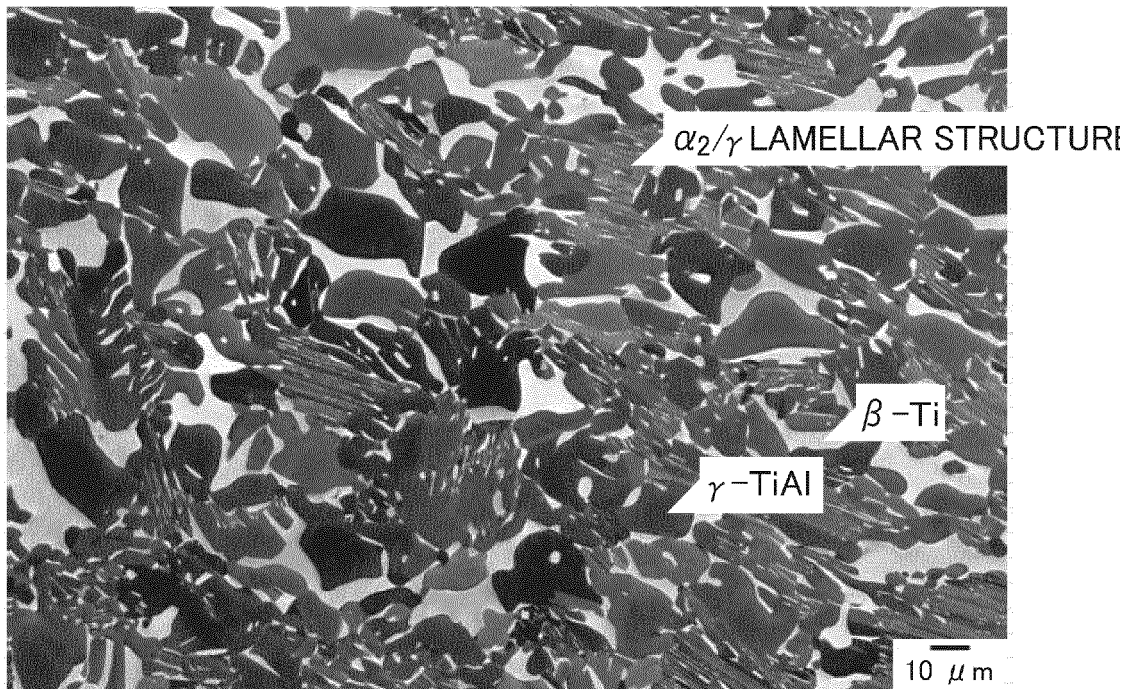


FIG. 5



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2020/007922

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. C22C14/00 (2006.01)i, B21J5/00 (2006.01)i, C22F1/18 (2006.01)i, C22F1/00 (2006.01)n
 FI: C22C14/00 Z, B21J5/00 E, C22F1/18 H, C22F1/00 624, C22F1/00 630A, C22F1/00 630K, C22F1/00 650A,
 C22F1/00 682, C22F1/00 683, C22F1/00 691B, C22F1/00 691C, C22F1/00 694B, C22F1/00 694Z

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. C22C14/00, B21J5/00, C22F1/18, C22F1/00

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 1971-2020

Registered utility model specifications of Japan 1996-2020

Published registered utility model applications of Japan 1994-2020

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	JP 8-120372 A (MITSUBISHI HEAVY INDUSTRIES, LTD.)	1
A	14 May 1996, paragraphs [0007]-[0014], table A	2-8
X	CN 103409660 A (NANJING UNIVERSITY OF SCIENCE AND TECHNOLOGY) 27 November 2013, paragraphs [0043], [0044], fig. 7-9	2
A		1, 3-8
X	JP 2016-166418 A (LEISTRITZ TURBINENTECHNIK GMBH)	1-5
A	15 September 2016, paragraphs [0006]-[0018]	6-8
A	JP 2015-4092 A (INDEPENDENT ADMINISTRATIVE INSTITUTION NATIONAL INSTITUTE FOR MATERIALS SCIENCE) 08 January 2015	1-8



Further documents are listed in the continuation of Box C.



See patent family annex.

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later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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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

15.05.2020

Date of mailing of the international search report

02.06.2020

Name and mailing address of the ISA/
 Japan Patent Office
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 Tokyo 100-8915, Japan

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INTERNATIONAL SEARCH REPORT

International application No. PCT/JP2020/007922
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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 6-116691 A (MITSUBISHI MATERIALS CORP.) 26 April 1994	1-8

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INTERNATIONAL SEARCH REPORT
 Information on patent family members

 International application No.
 PCT/JP2020/007922

Patent Documents referred to in the Report	Publication Date	Patent Family	Publication Date
JP 8-120372 A	14.05.1996	(Family: none)	
CN 103409660 A	27.11.2013	(Family: none)	
JP 2016-166418 A	15.09.2016	US 2016/0265096 A1 paragraphs [0006]- [0038] EP 3067435 A1 DE 102015103422 B3 PL 3067435 T3	
JP 2015-4092 A	08.01.2015	US 2016/0145703 A1 WO 2014/203714 A1 EP 3012337 A1	
JP 6-116691 A	26.04.1994	(Family: none)	

REFERENCES CITED IN THE DESCRIPTION

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- JP 2015004092 A [0002] [0003]
- JP 2009144247 A [0002] [0003]
- JP H05255781 A [0003]