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(54) **METAL POWDER FOR POWDER METALLURGY, COMPOUND, GRANULATED POWDER, AND SINTERED BODY**

(71) Applicant: **Seiko Epson Corporation**, Tokyo (JP)

(72) Inventor: **Hidefumi Nakamura**, Hachinohe (JP)

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(57) **ABSTRACT**

A metal powder comprising particles, which contain Fe, Cr, C and Si, and in which when one element selected from the group consisting of Ti, V, Y, Zr, Nb, Hf, and Ta is defined as a first element, and one element selected from the group consisting of Ti, V, Y, Zr, Nb, Hf, and Ta, and having a higher group number in the periodic table than that of the first element or having the same group number in the periodic table as that of the first element and a higher period number in the periodic table than that of the first element is defined as a second element, the first element is contained in a proportion of 0.01% by mass or more and 0.5% by mass or less, and the second element is contained in a proportion of 0.01% by mass or more and 0.5% by mass or less.

FIG. 1

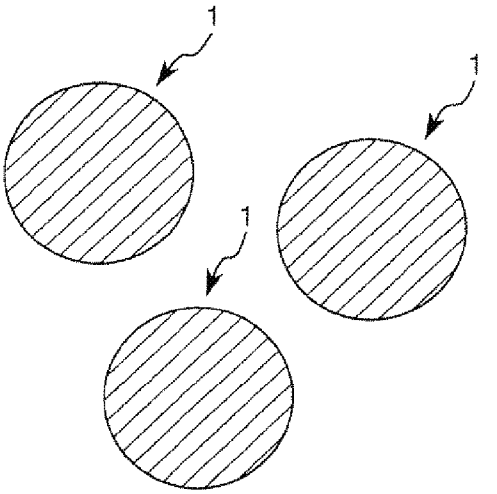


FIG. 2

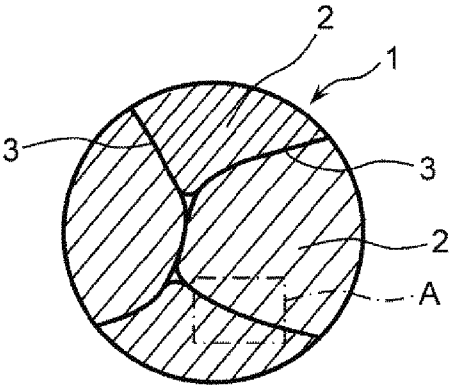


FIG. 3

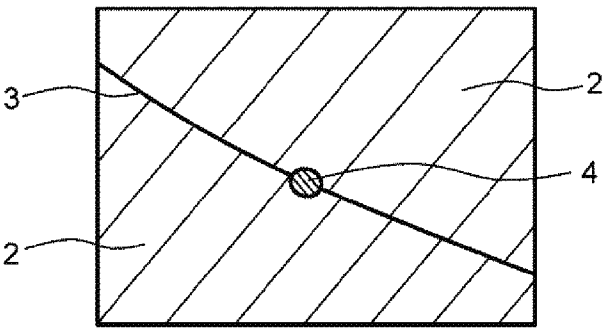


FIG. 4A

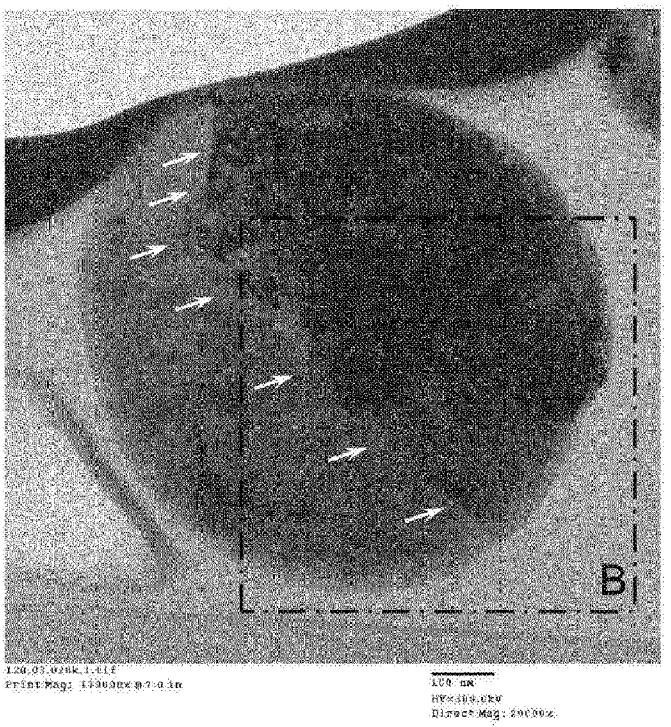
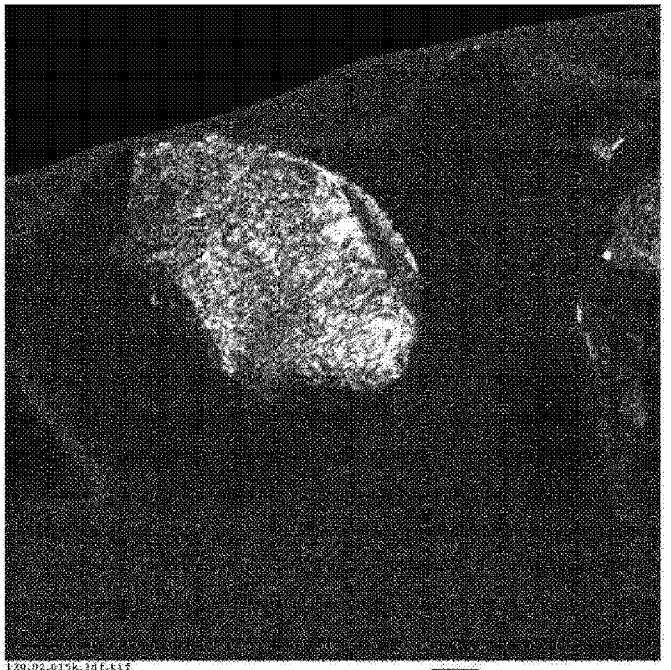


FIG. 4B



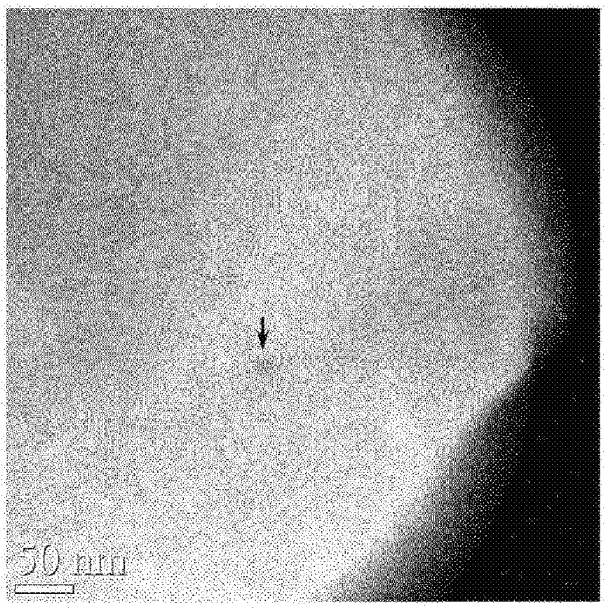
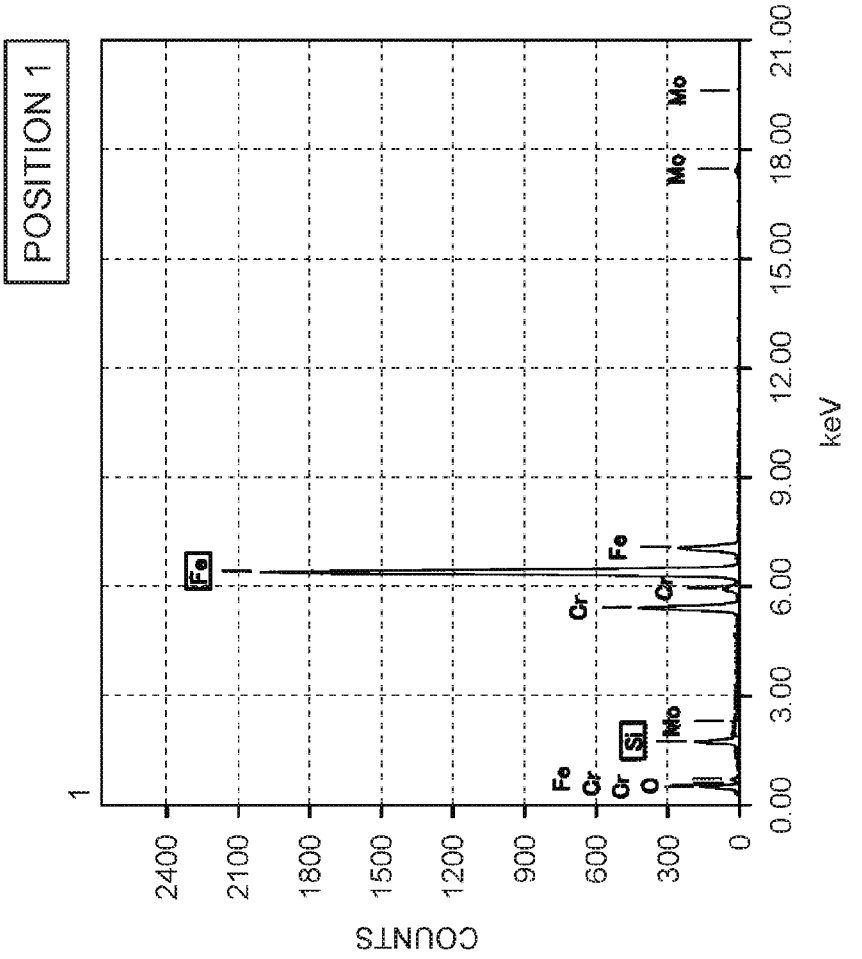


FIG. 5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3.00
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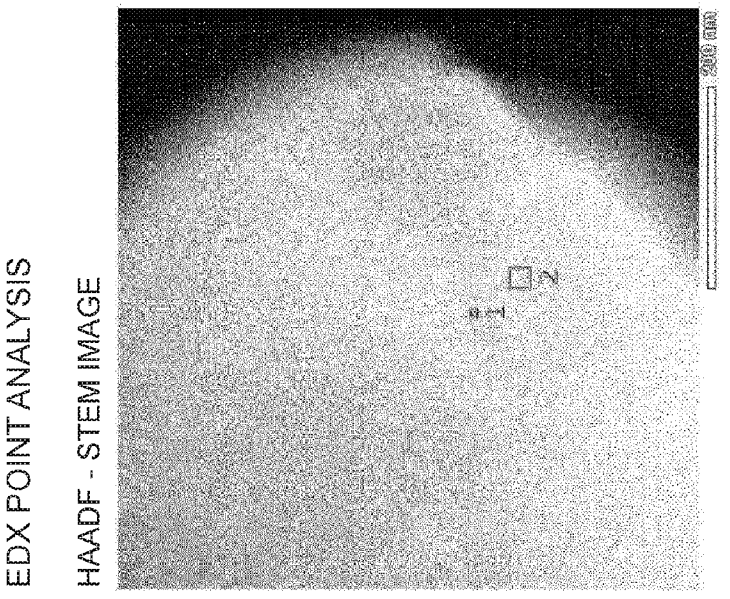
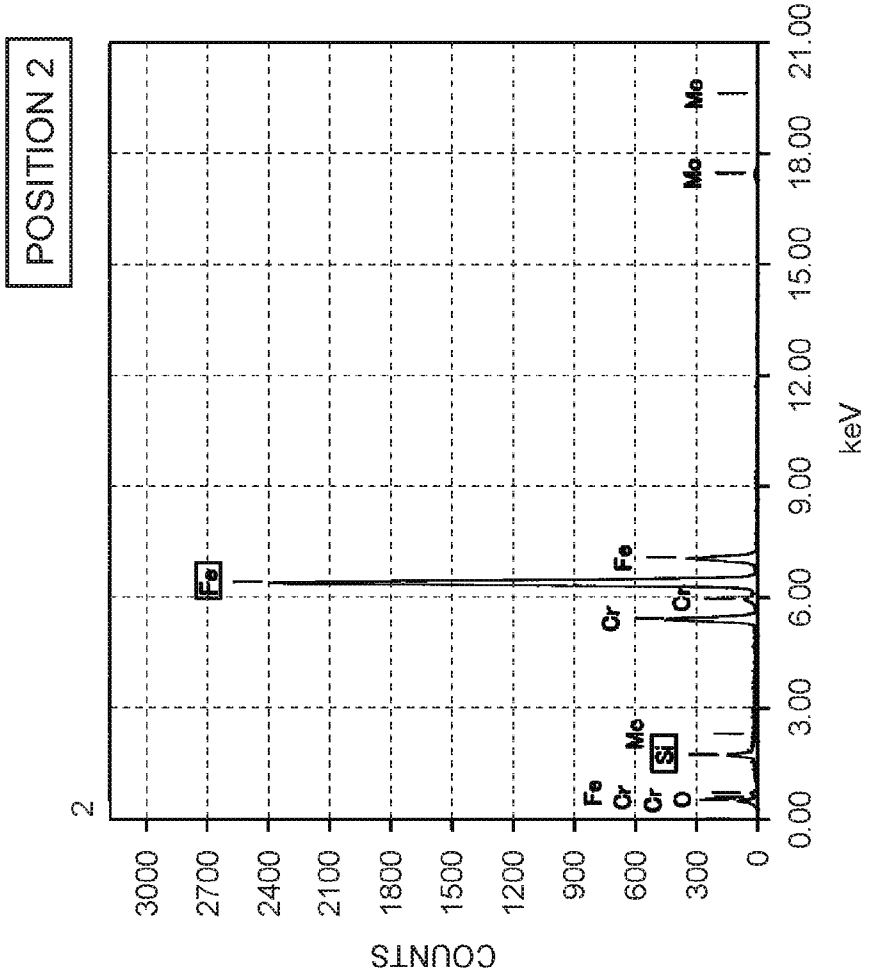

EDX POINT ANALYSIS
HAADF - STEM IMAGE
1
2

FIG. 6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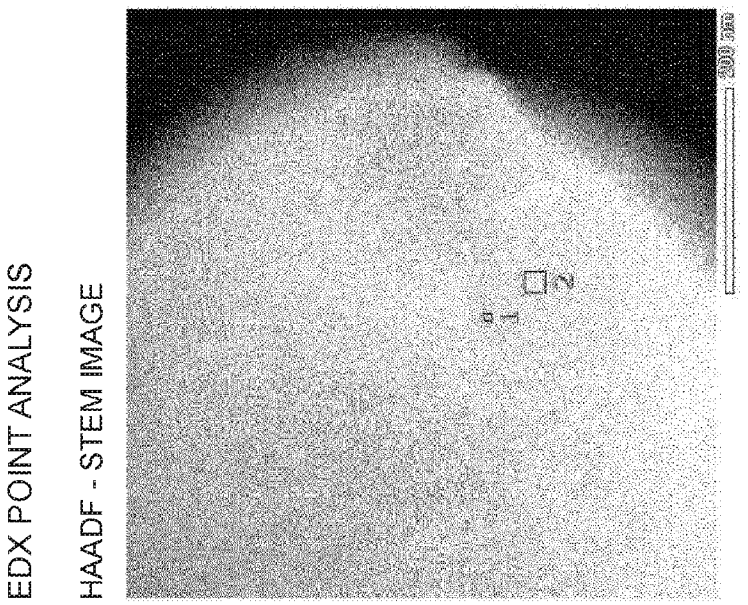

EDX POINT ANALYSIS
HAADF - STEM IMAGE
1
2

FIG. 7

FIG. 8A

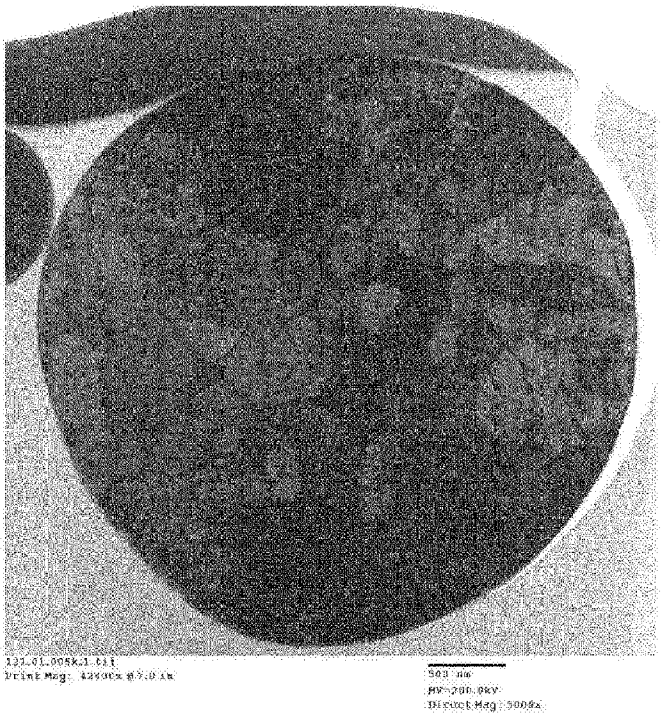
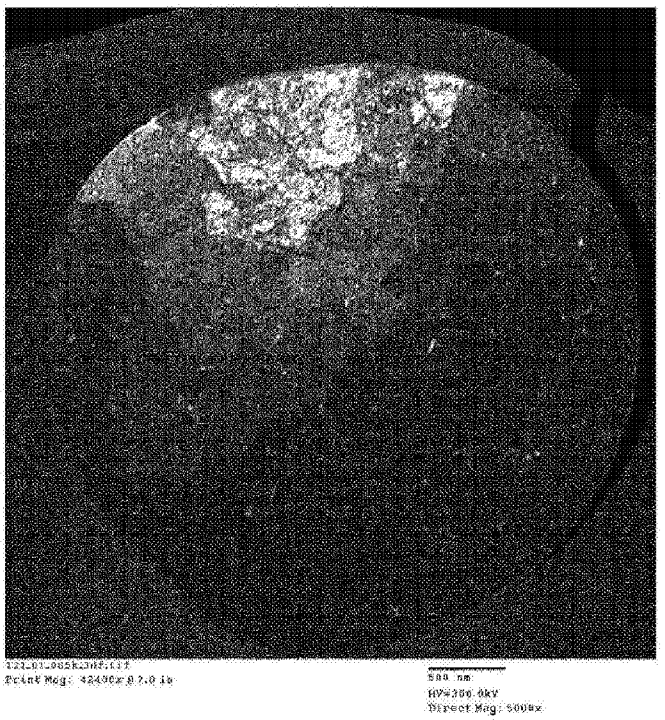


FIG. 8B



METAL POWDER FOR POWDER METALLURGY, COMPOUND, GRANULATED POWDER, AND SINTERED BODY

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to Japanese Patent Application No. 2015-016091 filed on Jan. 29, 2015. The entire disclosure of Japanese Patent Application No. 2015-016091 is hereby incorporated herein by reference.

BACKGROUND

[0002] 1. Technical Field

[0003] The present invention relates to a metal powder for powder metallurgy, a compound, a granulated powder, and a sintered body.

[0004] 2. Related Art

[0005] In a powder metallurgy method, a composition containing a metal powder and a binder is molded into a desired shape to obtain a molded body, and the obtained molded body is degreased and sintered, whereby a sintered body is produced. In such a process for producing a sintered body, an atomic diffusion phenomenon occurs among particles of the metal powder, whereby the molded body is gradually densified, resulting in sintering.

[0006] For example, JP-A-2012-87416 proposes a metal powder for powder metallurgy which contains Zr and Si, with the remainder including at least one element selected from the group consisting of Fe, Co, and Ni, and inevitable elements. According to such a metal powder for powder metallurgy, the sinterability is enhanced by the action of Zr, and a sintered body having a high density can be easily produced.

[0007] The thus obtained sintered body has recently become widely used for a variety of machine parts, structural parts, and the like.

[0008] However, depending on the use of a sintered body, further densification is needed in some cases. In such a case, a sintered body is further subjected to an additional treatment such as a hot isostatic pressing treatment (HIP treatment) to increase the density, however, the workload is significantly increased, and also an increase in the cost is inevitable.

[0009] Therefore, an expectation for realization of a metal powder capable of producing a sintered body having a high density without performing an additional treatment or the like has increased.

SUMMARY

[0010] An advantage of some aspects of the invention is to provide a metal powder for powder metallurgy, a compound, and a granulated powder, each of which is capable of producing a sintered body having a high density, and a sintered body having a high density.

[0011] The advantage can be achieved by aspects of the invention described below.

[0012] A metal powder for powder metallurgy according to an aspect of the invention includes particles, which contain Fe as a principal component, Cr in a proportion of 10% by mass or more and 30% by mass or less, C in a proportion of 0.1% by mass or more and 2% by mass or less, and Si in a proportion of 0.2% by mass or more and 1.5% by mass or less, and in which when one element selected from the group consisting of Ti, V, Y, Zr, Nb, Hf, and Ta is defined as a first element, and one element selected from the group consisting of Ti, V, Y, Zr, Nb, Hf, and Ta, and having a higher group number in the periodic table than that of the first element or having the same group number in the periodic table as that of the first element and a higher period number in the periodic table than that of the first element is defined as a second element, the first element is contained in a proportion of 0.01% by mass or more and 0.5% by mass or less and the second element is contained in a proportion of 0.01% by mass or more and 0.5% by mass or less, wherein the number of crystals in the cross section of the particle is 1 or more and 5 or less on average.

[0013] According to this, a metal powder for powder metallurgy capable of producing a sintered body having a high density is obtained.

[0014] In the metal powder for powder metallurgy according to the aspect of the invention, it is preferred that the crystal contains Fe as a principal component, and the particle further includes a region, which has a smaller volume than the crystal, and in which the ratio of the content of Si to the content of Fe is higher than in the crystal.

[0015] According to this, a metal powder for powder metallurgy capable of producing a sintered body having a high relative density and excellent mechanical properties is obtained.

[0016] In the metal powder for powder metallurgy according to the aspect of the invention, it is preferred that in the cross section of the particle, the circle equivalent diameter of the crystal is 1% or more and 100% or less the circle equivalent diameter of the particle.

[0017] According to this, the crystal can dominantly behave with respect to the sinterability of the particles when they are fired. That is, the particles behave as if they were single crystal grains, and therefore, the sintering rate is increased, and thus, this configuration greatly contributes to an increase in the sintered density.

[0018] In the metal powder for powder metallurgy according to the aspect of the invention, it is preferred that the crystal has a martensite crystal structure.

[0019] The martensite crystal structure includes a body-centered cubic lattice in the form of a solid solution supersaturated with, for example, C. This body-centered cubic lattice is formed by transformation from a face-centered cubic lattice accompanying firing or a heat treatment after firing, and the volume thereof is expanded at that time. Therefore, a metal powder for powder metallurgy having a martensite crystal structure is capable of producing a sintered body having a high hardness.

[0020] A compound according to an aspect of the invention includes the metal powder for powder metallurgy according to the aspect of the invention and a binder which binds the particles of the metal powder for powder metallurgy to one another.

[0021] According to this, a compound capable of producing a sintered body having a high density is obtained.

[0022] A granulated powder according to an aspect of the invention is obtained by granulating the metal powder for powder metallurgy according to the aspect of the invention.

[0023] According to this, a granulated powder capable of producing a sintered body having a high density is obtained.

[0024] A sintered body according to an aspect of the invention is produced by sintering the metal powder for powder metallurgy according to the aspect of the invention.

[0025] According to this, a sintered body having a high density is obtained.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The invention will be described with reference to the accompanying drawings, wherein like numbers reference like elements.

[0027] FIG. **1** is a view schematically showing the cross sections of particles contained in an embodiment of a metal powder for powder metallurgy according to the invention.

[0028] FIG. **2** is a view schematically showing the crystal structure of the particle shown in FIG. **1**.

[0029] FIG. **3** is an enlarged view of an area A surrounded by the dashed line in FIG. **2**.

[0030] FIG. **4**A shows one example of a TEM image (bright field image) of the cross section of a particle **1**, and FIG. **4**B shows one example of a TEM image (dark field image) of the cross section of the particle **1** shown in FIG. **4**A.

[0031] FIG. **5** is a partial enlarged view of an area B surrounded by the dashed line shown in FIG. **4**A and is an observation image when the area B was observed with a high-angle annular dark field scanning transmission electron microscope.

[0032] FIG. **6** shows one example of the EDX spectrum of a high Si concentration region shown in FIG. **5** and shows a spectrum obtained by a point analysis at a position (Position 1 in FIG. **6**) corresponding to the high Si concentration region shown in FIG. **5**.

[0033] FIG. **7** shows one example of the EDX spectrum of an Fe-based alloy crystal shown in FIG. **5** and shows a spectrum obtained by a point analysis at a position (Position 2 in FIG. **7**) corresponding to the Fe-based alloy crystal shown in FIG. **5**.

[0034] FIG. **8**A shows one example of a TEM image (bright field image) of the cross section of a particle containing 6 or more Fe-based alloy crystals, and FIG. **8**B shows one example of a TEM image (dark field image) of the cross section of the particle shown in FIG. **8**A.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0035] Hereinafter, a metal powder for powder metallurgy, a compound, a granulated powder, and a sintered body according to the invention will be described in detail with reference to preferred embodiments shown in the accompanying drawings.

Metal Powder for Powder Metallurgy

[0036] First, a metal powder for powder metallurgy according to the invention will be described.

[0037] In powder metallurgy, a sintered body having a desired shape can be obtained by molding a composition containing a metal powder for powder metallurgy and a binder into a desired shape, followed by degreasing and firing. According to such a powder metallurgy technique, a sintered body with a complicated and fine shape can be produced in a near-net shape (a shape close to a final shape) as compared with the other metallurgy techniques.

[0038] With respect to the metal powder for powder metallurgy to be used in the powder metallurgy, an attempt to increase the density of a sintered body to be produced by appropriately changing the composition thereof has been made. However, in the sintered body, pores are liable to be generated, and therefore, in order to obtain mechanical properties comparable to those of ingot materials, it was necessary to further increase the density of the sintered body.

[0039] For example, in the past, the obtained sintered body was further subjected to an additional treatment such as a hot isostatic pressing treatment (HIP treatment) to increase the density. However, such an additional treatment requires much time, labor, and cost, and therefore becomes an obstacle to the expansion of the application of the sintered body.

[0040] In consideration of the above-mentioned problems, the present inventors have made intensive studies to find conditions for obtaining a sintered body having a high density without performing an additional treatment. As a result, they found that the density of a sintered body can be increased by optimizing the chemical composition and the crystal structure of each particle contained in a metal powder, and thus completed the invention.

[0041] Specifically, the metal powder for powder metallurgy according to this embodiment includes particles, which contain Fe as a principal component, Cr in a proportion of 10% by mass or more and 30% by mass or less, C in a proportion of 0.1% by mass or more and 2% by mass or less, Si in a proportion of 0.2% by mass or more and 1.5% by mass or less, the below-mentioned first element in a proportion of 0.01% by mass or more and 0.5% by mass or less, and the below-mentioned second element in a proportion of 0.01% by mass or more and 0.5% by mass or less. Further, the number of crystals in the cross section of the particle is 1 or more and 5 or less on average. According to the metal powder for powder metallurgy containing such particles, when the particles are sintered in a firing step, the sintering is promoted and densification proceeds. As a result, a sintered body having a sufficiently high density can be produced without performing an additional treatment.

[0042] Such a sintered body has excellent mechanical properties. Due to this, the sintered body can be widely applied also to, for example, machine parts, structural parts, and the like, to which an external force is applied.

[0043] The first element is one element selected from the group consisting of the following seven elements: Ti, V, Y, Zr, Nb, Hf, and Ta, and the second element is one element selected from the group consisting of the above-mentioned seven elements and having a higher group number in the periodic table than that of the first element or one element selected from the group consisting of the above-mentioned seven elements and having the same group number in the periodic table as that of the element selected as the first element and a higher period number in the periodic table than that of the first element.

[0044] Hereinafter, the configuration of the metal powder for powder metallurgy according to this embodiment will be described in further detail. In the following description, the "metal powder for powder metallurgy" is sometimes simply referred to as "metal powder", and each of the multiple particles constituting the metal powder for powder metallurgy is sometimes simply referred to as "particle".

[0045] FIG. **1** is a view schematically showing the cross sections of particles contained in an embodiment of the metal powder for powder metallurgy according to the invention, and FIG. **2** is a view schematically showing the crystal structure of the particle shown in FIG. **1**.

[0046] A particle **1** shown in FIG. **1** is constituted by an Fe-based alloy. As shown in FIG. **2**, the particle **1** includes one or more and 5 or less crystals on average in the cross section.

[0047] The crystal is preferably a crystal containing Fe as a principal component. Then, these crystals occupy most (90% or more in terms of area ratio) of the cross section of the

particle **1**. Therefore, these crystals have an influence on the properties of the particle **1** (metal powder for powder metallurgy) and the properties of a sintered body to be produced from the particle **1**.

[0048] That is, the particle **1** is a particle having a very small number of Fe-based alloy crystals contained therein. Such a particle **1** can be said to be single-crystalline or polycrystalline close to single-crystalline, and behaves in the same manner as a single crystal when it is fired. Therefore, when the metal powder for powder metallurgy is fired, sintering proceeds at an excellent sintering rate derived from the single crystal. As a result, a sintered body having few internal gaps and a high relative density can be produced.

[0049] The clause "Fe is contained as a principal component in the crystal" refers to a state in which Fe is an element contained at the highest concentration in a local chemical composition of the crystal. The chemical composition of the crystal can be determined by, for example, a qualitative and quantitative analysis by energy dispersive X-ray spectrometry.

[0050] The cross-sectional view of the particle **1** shown in FIG. **2** is an example showing the presence of typical crystals among many particles contained in the metal powder for powder metallurgy.

[0051] The particle **1** shown in FIG. **2** includes four Fe-based alloy crystals **2**. The adjacent Fe-based alloy crystals **2** are separated by a linear grain boundary **3**.

[0052] As described above, the particle **1** includes 1 or more and 5 or less Fe-based alloy crystals **2** on average in the cross section of the particle.

[0053] The average number of the Fe-based alloy crystals **2** in the cross section of the particle **1** is a value obtained by observing the cross sections of 10 or more particles **1** contained in the metal powder as observation targets with an electron microscope, counting the number of the Fe-based alloy crystals **2** contained in each particle **1** by visual observation of an observation image, and averaging the counts in all the observation targets. As the electron microscope, for example, a transmission electron microscope (TEM) is used, and the observation can be performed in a bright field image. When it is difficult to clearly specify the grain boundary **3** in the bright field image, the grain boundary **3** may be easily specified by changing the bright field image into a dark field image in some cases.

[0054] The circle equivalent diameter of the Fe-based alloy crystal **2** (the diameter of a circle having the same area as that of the cross section of the Fe-based alloy crystal **2**) is preferably 1% or more and 100% or less, more preferably 3% or more and less than 100% of the circle equivalent diameter of the particle **1** (the diameter of a circle having the same area as that of the cross section of the particle **1**). When the ratio of the crystal grain diameter of the Fe-based alloy crystal **2** to the diameter of the particle **1** falls within the above range, the Fe-based alloy crystal **2** can dominantly behave with respect to the sinterability of the particles **1** when they are fired. That is, the particle **1** behaves as if it was a single crystal grain, and therefore, the sintering rate is increased, and thus, this configuration greatly contributes to an increase in the sintered density.

[0055] FIG. **3** is an enlarged view of an area A surrounded by the dashed line in FIG. **2**.

[0056] In the area A shown in FIG. **3**, a high Si concentration region **4**, which has a smaller volume than the Fe-based alloy crystal **2**, and in which the ratio of the content of Si to the content of Fe is higher than in the Fe-based alloy crystal **2**, is present. By the presence of such a high Si concentration region **4**, a sintered body produced by using the metal powder containing the particle **1** has a high relative density and excellent mechanical properties.

[0057] The high Si concentration region **4** is a region, which is present in the inside of the Fe-based alloy crystal **2** or at the grain boundary **3**, and in which the ratio of the content of Si to the content of Fe is higher than in the Fe-based alloy crystal **2**. The contents of these elements can be determined by, for example, the qualitative and quantitative analysis of each of the Fe-based alloy crystal **2** and the high Si concentration region **4** by energy dispersive X-ray spectrometry (EDX). Further, as a simple way, the height of a peak of Fe located at near 6.4 keV and the height of a peak of Si located at near 1.8 keV in the EDX spectrum are determined, and the ratio of the height of the peak of Si to the height of the peak of Fe is calculated, whereby the ratio of the content of Si to the content of Fe can be obtained.

[0058] Therefore, when the content of Fe in the Fe-based alloy crystal **2** is represented by Fe(2), the content of Si therein is represented by Si(2), the content of Fe in the high Si concentration region **4** is represented by Fe(4), and the content of Si therein is represented by Si(4), the particle **1** satisfies the following formula (1).

$$Si(2)/Fe(2)<Si(4)/Fe(4) \quad (1)$$

[0059] The position of the high Si concentration region **4** in the cross section of the particle **1** is not particularly limited, but is preferably at the grain boundary **3**. According to this, the sintering rate of the Fe-based alloy crystal **2** is particularly increased, and thus, a sintered body having a particularly high relative density can be produced.

[0060] The shape of the high Si concentration region **4** in the cross section of the particle **1** is not particularly limited and may be any shape, but is preferably a circle, a polygon, or a shape equivalent thereto. By including the high Si concentration region **4** in such a shape, the sinterability of the particle **1** is further enhanced, and the relative density of a sintered body produced by using the metal powder containing such particles **1** is further increased.

[0061] In other words, the shape of the high Si concentration region **4** is preferably a shape having a low aspect ratio. Specifically, the average of the aspect ratio defined by the major axis/minor axis of the high Si concentration region **4** is preferably 1 or more and 3 or less, more preferably 1 or more and 2 or less. By including the high Si concentration region **4** in such a shape, the sinterability of the particle **1** is further enhanced, and the relative density of a sintered body produced by using the metal powder containing such particles **1** is further increased in the same manner as described above.

[0062] The "major axis" of the high Si concentration region **4** is the maximum length of the high Si concentration region **4**, and the "minor axis" is the maximum length in the direction perpendicular to the major axis.

[0063] Further, the particle **1** preferably satisfies the following formula (2), more preferably satisfies the following formula (3).

$$1.2\times Si(2)/Fe(2)<Si(4)/Fe(4)<1 \quad (2)$$

$$1.3\times Si(2)/Fe(2)<Si(4)/Fe(4)<0.8 \quad (3)$$

[0064] Here, FIG. **4**A shows one example of a TEM image (bright field image) of the cross section of the particle **1**, and

FIG. **4**B shows one example of a TEM image (dark field image) of the cross section of the particle **1** shown in FIG. **4**A.

[0065] In the TEM image (bright field image) shown in FIG. **4**A, two Fe-based alloy crystals **2** contained in the particle **1** are shown. Further, a line based on a difference in shading indicated by the arrows in FIG. **4**A is the grain boundary **3** located on a boundary between the two Fe-based alloy crystals **2**.

[0066] Further, in the TEM image (dark field image) shown in FIG. **4**B, among the two Fe-based alloy crystals **2**, one Fe-based alloy crystal **2** located on the upper right side appears in a light color and the other Fe-based alloy crystal **2** located on the lower left side appears in a dark color. By observing the Fe-based alloy crystals **2** in the dark field image, the contrast between the two Fe-based alloy crystals **2** can be enhanced based on the difference in the type of crystal.

[0067] Further, FIG. **5** is a partial enlarged view of an area B surrounded by the dashed line shown in FIG. **4**A and is an observation image when the area B was observed with a high-angle annular dark field scanning transmission electron microscope. A dark color portion indicated by the arrow in FIG. **5** is the high Si concentration region **4**. By comparison of FIGS. **4**A and **4**B with FIG. **5**, it is found that the high Si concentration region **4** is located at the grain boundary **3**.

[0068] FIG. **6** shows one example of the EDX spectrum of the high Si concentration region **4** shown in FIG. **5** and shows a spectrum obtained by a point analysis at a position (Position 1 in FIG. **6**) corresponding to the high Si concentration region **4** shown in FIG. **5**. Further, FIG. **7** shows one example of the EDX spectrum of the Fe-based alloy crystal **2** shown in FIG. **5** and shows a spectrum obtained by a point analysis at a position (Position 2 in FIG. **7**) corresponding to the Fe-based alloy crystal **2** shown in FIG. **5**.

[0069] As shown in these examples of the EDX spectra, according to the EDX spectrum at the position corresponding to the high Si concentration region **4**, it is shown that the amount of Si is increased with respect to the amount of Fe as compared with that at the position corresponding to the Fe-based alloy crystal **2**.

[0070] On the other hand, FIG. **8**A shows one example of a TEM image (bright field image) of the cross section of a particle containing 6 or more Fe-based alloy crystals, and FIG. **8**B shows one example of a TEM image (dark field image) of the cross section of the particle shown in FIG. **8**A. The particle shown in FIGS. **8**A and **8**B has a chemical composition containing no first element or second element described above and corresponds to Comparative Example with respect to the invention.

[0071] As shown in FIGS. **8**A and **8**B, in the particle having a chemical composition containing no first element or second element, many crystals are generated. Such a particle can be said to be polycrystalline close to microcrystalline, and behaves in a different manner from a single crystal when it is fired. Therefore, when the metal powder containing such particles is fired, the sintering rate is decreased, resulting in decreasing the relative density of a sintered body.

[0072] The Fe-based alloy crystal **2** preferably has a martensite crystal structure. The martensite crystal structure includes a body-centered cubic lattice in the form of a solid solution supersaturated with, for example, C. This body-centered cubic lattice is formed by transformation from a face-centered cubic lattice accompanying firing or a heat treatment after firing, and the volume thereof is expanded at that time. Therefore, the Fe-based alloy crystal **2** having a martensite crystal structure enables the production of a sintered body having a high hardness.

[0073] It can be determined whether or not the metal powder for powder metallurgy has a martensite crystal structure by, for example, X-ray diffractometry.

[0074] Hereinafter, one example of the chemical composition of the particle **1** will be described in further detail.

[0075] In the chemical composition of the whole particle **1**, Fe is an element (principal component) whose content is the highest and has an influence on the properties of the sintered body. The content of Fe in the whole particle **1** is 50% by mass or more.

Cr

[0076] Cr (chromium) is an element which provides corrosion resistance to a sintered body to be produced. By using the metal powder containing Cr, a sintered body capable of maintaining high mechanical properties over a long period of time is obtained.

[0077] The content of Cr in the particle **1** is set to 10% by mass or more and 30% by mass or less, but is set to preferably 10.5% by mass or more and 20% by mass or less, more preferably 11% by mass or more and 18% by mass or less. If the content of Cr is less than the above lower limit, the corrosion resistance of a sintered body to be produced may be insufficient depending on the overall composition. On the other hand, if the content of Cr exceeds the above upper limit, the sinterability is deteriorated depending on the overall composition so that it may become difficult to increase the density of the sintered body.

C

[0078] C (carbon) can particularly enhance the sinterability when it is used in combination with the below-mentioned first element and second element.

[0079] Specifically, the first element and the second element each form a carbide by binding to C. By dispersedly depositing this carbide, an effect of preventing the significant growth of crystal grains is exhibited. A clear reason for obtaining such an effect has not been known, but one of the reasons therefor is considered to be because the dispersed deposit serves as an obstacle to inhibit the significant growth of crystal grains, and therefore, a variation in the size of crystal grains is suppressed. Accordingly, it becomes difficult to generate pores in a sintered body, and also the increase in the size of crystal grains is prevented, and thus, a sintered body having a high density and excellent mechanical properties is obtained.

[0080] The content of C in the particle **1** is set to 0.1% by mass or more and 2% by mass or less, but is set to preferably 0.35% by mass or more and 1.15% by mass or less, more preferably 0.4% by mass or more and 1.1% by mass or less. If the content of C is less than the above lower limit, crystal grains are liable to grow depending on the overall composition so that the mechanical properties of the sintered body are insufficient. On the other hand, if the content of C exceeds the above upper limit, the amount of C is too large depending on the overall composition so that the sinterability is deteriorated instead.

Si

[0081] Si (silicon) is an element which provides corrosion resistance and high mechanical properties to a sintered body to be produced, and by using the metal powder containing Si, a sintered body capable of maintaining high mechanical properties over a long period of time can be obtained.

[0082] The content of Si in the particle **1** is set to 0.2% by mass or more and 1.5% by mass or less, but is set to preferably 0.3% by mass or more and 1% by mass or less, more preferably 0.5% by mass or more and 0.8% by mass or less. If the content of Si is less than the above lower limit, the effect of the addition of Si is weakened depending on the overall composition so that the corrosion resistance and the mechanical properties of a sintered body to be produced may be deteriorated. On the other hand, if the content of Si exceeds the above upper limit, the amount of Si is too large depending on the overall composition so that the corrosion resistance and the mechanical properties may be deteriorated instead.

Mn

[0083] Mn is an element which is added as needed and provides corrosion resistance and high mechanical properties to a sintered body to be produced in the same manner as Si.

[0084] The content of Mn in the particle **1** is not particularly limited, but is preferably 0.01% by mass or more and 1.25% by mass or less, more preferably 0.03% by mass or more and 0.3% by mass or less, further more preferably 0.05% by mass or more and 0.2% by mass or less. By setting the content of Mn within the above range, a sintered body having a high density and excellent mechanical properties is obtained. Further, Mn can increase the mechanical strength while suppressing the decrease in elongation. Further, Mn can suppress the increase in brittleness at a high temperature (when glowing).

[0085] If the content of Mn is less than the above lower limit, the corrosion resistance and the mechanical properties of a sintered body to be produced may not be sufficiently enhanced depending on the overall composition. On the other hand, if the content of Mn exceeds the above upper limit, the corrosion resistance and the mechanical properties may be deteriorated instead.

Ni

[0086] Ni is an element which is added as needed and provides corrosion resistance and heat resistance to a sintered body to be produced.

[0087] The content of Ni in the particle **1** is not particularly limited, but is preferably 0.05% by mass or more and 0.6% by mass or less, more preferably 0.06% by mass or more and 0.4% by mass or less, further more preferably 0.07% by mass or more and 0.25% by mass or less. By setting the content of Ni within the above range, a sintered body which maintains excellent mechanical properties over a long period of time can be obtained.

[0088] If the content of Ni is less than the above lower limit, the corrosion resistance and the heat resistance of a sintered body to be produced may not be sufficiently enhanced depending on the overall composition. On the other hand, if the content of Ni exceeds the above upper limit, the corrosion resistance and the heat resistance may be deteriorated instead.

[0089] Further, Mn and Ni are contained in a total proportion of preferably 0.05% by mass or more and 1.6% by mass or less, more preferably 0.08% by mass or more and 1.3% by mass or less, further more preferably 0.1% by mass or more and 1% by mass or less. According to this, the mechanical properties of the sintered body can be particularly enhanced.

First Element and Second Element

[0090] The first element and the second element each deposit a carbide or an oxide (hereinafter also collectively referred to as "carbide or the like"). It is considered that this deposited carbide or the like inhibits the significant growth of crystal grains when the metal powder is sintered. As a result, as described above, it becomes difficult to generate pores in a sintered body, and also the increase in the size of crystal grains is prevented, and thus, a sintered body having a high density and excellent mechanical properties is obtained.

[0091] In addition, although a detailed description will be given later, the deposited carbide or the like promotes the accumulation of silicon oxide at a crystal grain boundary, and as a result, the sintering is promoted and the density is increased while preventing the increase in the size of crystal grains.

[0092] The first element and the second element are two elements selected from the group consisting of the following seven elements: Ti, V, Y, Zr, Nb, Hf, and Ta, but preferably include an element belonging to group III A or group IV A in the long periodic table (Ti, Y, Zr, or Hf). By including an element belonging to group III A or group IV A as at least one of the first element and the second element, oxygen contained as an oxide in the metal powder is removed and the sinterability of the metal powder can be particularly enhanced.

[0093] The first element is only required to be one element selected from the group consisting of the following seven elements: Ti, V, Y, Zr, Nb, Hf, and Ta as described above, but is preferably an element belonging to group III A or group IV A in the long periodic table in the group consisting of the above-mentioned seven elements. An element belonging to group 3A or group 4A removes oxygen contained as an oxide in the metal powder and therefore can particularly enhance the sinterability of the metal powder. According to this, the concentration of oxygen remaining in the crystal grains after sintering can be decreased. As a result, the content of oxygen in the sintered body can be decreased, and the density can be increased. Further, these elements are elements having high activity, and therefore are considered to cause rapid atomic diffusion. Accordingly, this atomic diffusion acts as a driving force, and thereby a distance between particles of the metal powder is efficiently decreased and a neck is formed between the particles, so that the densification of a molded body is promoted. As a result, the density of the sintered body can be further increased.

[0094] On the other hand, the second element is only required to be one element selected from the group consisting of the following seven elements: Ti, V, Y, Zr, Nb, Hf, and Ta and different from the first element as described above, but is preferably an element belonging to group V A in the long periodic table in the group consisting of the above-mentioned seven elements. An element belonging to group V A particularly efficiently deposits the above-mentioned carbide or the like, and therefore, can efficiently inhibit the significant growth of crystal grains during sintering. As a result, the formation of fine crystal grains is promoted, and thus, the density of the sintered body can be increased and also the mechanical properties of the sintered body can be enhanced.

[0095] Incidentally, by the combination of the first element with the second element composed of the elements as

described above, the effects of the respective elements are exhibited without inhibiting each other. Due to this, the metal powder containing such a first element and a second element enables the production of a sintered body having a particularly high density.

[0096] More preferably, a combination of an element belonging to group 4A as the first element with Nb as the second element is adopted.

[0097] Further, more preferably, a combination of Zr or Hf as the first element with Nb as the second element is adopted.

[0098] By adopting such a combination, the above-mentioned effect becomes more prominent.

[0099] In the case where the first element is particularly Zr, Zr is a ferrite forming element, and therefore deposits a body-centered cubic lattice phase. This body-centered cubic lattice phase has more excellent sinterability than the other crystal lattice phases, and therefore contributes to the densification of a sintered body.

[0100] The atomic radius of Zr is slightly larger than that of Fe. Specifically, the atomic radius of Fe is about 0.117 nm, and the atomic radius of Zr is about 0.145 nm. Therefore, Zr is solid-dissolved in Fe, but is not completely solid-dissolved therein, and part of Zr is deposited as a carbide or the like. According to this, an appropriate amount of a carbide or the like is deposited, and therefore, the increase in the size of crystal grains can be effectively prevented while promoting the sintering and increasing the density.

[0101] In the case where the second element is particularly Nb, the atomic radius of Nb is slightly larger than that of Fe, but slightly smaller than that of Zr. Specifically, the atomic radius of Fe is about 0.117 nm, and the atomic radius of Nb is about 0.134 nm. Therefore, Nb is solid-dissolved in Fe, but is not completely solid-dissolved therein, and part of Nb is deposited as a carbide or the like. According to this, an appropriate amount of a carbide or the like is deposited, and therefore, the increase in the size of crystal grains can be effectively prevented while promoting the sintering and increasing the density.

[0102] The content of the first element in the particle **1** is set to 0.01% by mass or more and 0.5% by mass or less, but is set to preferably 0.03% by mass or more and 0.3% by mass or less, more preferably 0.05% by mass or more and 0.2% by mass or less. If the content of the first element is less than the above lower limit, the effect of the addition of the first element is weakened depending on the overall composition so that the density of a sintered body to be produced may not be sufficiently increased. On the other hand, if the content of the first element exceeds the above upper limit, the amount of the first element is too large depending on the overall composition so that the ratio of the above-mentioned carbide or the like is too high, and therefore, the densification may be deteriorated instead.

[0103] The content of the second element in the particle **1** is set to 0.01% by mass or more and 0.5% by mass or less, but is set to preferably 0.03% by mass or more and 0.3% by mass or less, more preferably 0.05% by mass or more and 0.2% by mass or less. If the content of the second element is less than the above lower limit, the effect of the addition of the second element is weakened depending on the overall composition so that the density of a sintered body to be produced may not be sufficiently increased. On the other hand, if the content of the second element exceeds the above upper limit, the amount of the second element is too large depending on the overall composition so that the ratio of the above-mentioned carbide or the like is too high, and therefore, the densification may be deteriorated instead.

[0104] Further, as described above, each of the first element and the second element deposits a carbide or the like, however, in the case where an element belonging to group III A or group IV A is selected as the first element as described above and an element belonging to group V A is selected as the second element as described above, it is presumed that when the metal powder is sintered, the timing when a carbide or the like of the first element is deposited and the timing when a carbide or the like of the second element is deposited differ from each other. It is considered that due to the difference in timing when a carbide or the like is deposited in this manner, sintering gradually proceeds so that the generation of pores is prevented, and thus, a dense sintered body is obtained. That is, it is considered that by the presence of both of the carbide or the like of the first element and the carbide or the like of the second element, the increase in the size of crystal grains can be suppressed while increasing the density of the sintered body.

[0105] In addition, it is considered that in the particle **1**, the carbide or the like of the first element and the carbide or the like of the second element act as "nuclei", and the accumulation of silicon oxide occurs. By the accumulation of silicon oxide in a crystal grain (in the Fe-based alloy crystal **2**) or at a crystal grain boundary (at the grain boundary **3**), the concentration of oxides inside the crystal is decreased, and therefore, sintering is promoted. As a result, it is considered that the densification of the sintered body is further promoted when the particles **1** are sintered.

[0106] The particle **1** is only required to contain two elements selected from the group consisting of the above-mentioned seven elements, but may further contain an element which is selected from this group and is different from these two elements. That is, the particle **1** may contain three or more elements selected from the group consisting of the above-mentioned seven elements. According to this, the above-mentioned effect can be further enhanced, which slightly varies depending on the combination of the elements to be contained.

[0107] Further, it is preferred to set the ratio of the content of the first element to the content of the second element in consideration of the mass number of the first element and the mass number of the second element.

[0108] Specifically, when a value obtained by dividing the content E1 (mass %) of the first element by the mass number of the first element is represented by X1 and a value obtained by dividing the content E2 (mass %) of the second element by the mass number of the second element is represented by X2, X1/X2 is preferably 0.3 or more and 3 or less, more preferably 0.5 or more and 2 or less, further more preferably 0.75 or more and 1.3 or less. By setting the ratio X1/X2 within the above range, the balance between the deposition amount of the carbide or the like of the first element and the deposition amount of the carbide or the like of the second element can be optimized. According to this, pores remaining in a molded body can be eliminated as if they were swept out sequentially from the inside, and therefore, pores generated in a sintered body can be minimized. Accordingly, a metal powder capable of producing a sintered body having a high density and excellent mechanical properties can be obtained by setting the ratio X1/X2 within the above range.

[0109] Here, with respect to a specific example of the combination of the first element with the second element, based on the above-mentioned range of the ratio X1/X2, the ratio (E1/E2) of the content E1 of the first element to the content E2 of the second element is calculated.

[0110] For example, in the case where the first element is Zr and the second element is Nb, since the mass number of Zr is 91.2 and the mass number of Nb is 92.9, E1/E2 is preferably 0.29 or more and 2.95 or less, more preferably 0.49 or more and 1.96 or less.

[0111] In the case where the first element is Hf and the second element is Nb, since the mass number of Hf is 178.5 and the mass number of Nb is 92.9, E1/E2 is preferably 0.58 or more and 5.76 or less, more preferably 0.96 or more and 3.84 or less.

[0112] In the case where the first element is Ti and the second element is Nb, since the mass number of Ti is 47.9 and the mass number of Nb is 92.9, E1/E2 is preferably 0.15 or more and 1.55 or less, more preferably 0.26 or more and 1.03 or less.

[0113] In the case where the first element is Nb and the second element is Ta, since the mass number of Nb is 92.9 and the mass number of Ta is 180.9, E1/E2 is preferably 0.15 or more and 1.54 or less, more preferably 0.26 or more and 1.03 or less.

[0114] In the case where the first element is Y and the second element is Nb, since the mass number of Y is 88.9 and the mass number of Nb is 92.9, E1/E2 is preferably 0.29 or more and 2.87 or less, more preferably 0.48 or more and 1.91 or less.

[0115] In the case where the first element is V and the second element is Nb, since the mass number of V is 50.9 and the mass number of Nb is 92.9, E1/E2 is preferably 0.16 or more and 1.64 or less, more preferably 0.27 or more and 1.10 or less.

[0116] In the case where the first element is Ti and the second element is Zr, since the mass number of Ti is 47.9 and the mass number of Zr is 91.2, E1/E2 is preferably 0.16 or more and 1.58 or less, more preferably 0.26 or more and 1.05 or less.

[0117] In the case where the first element is Zr and the second element is Ta, since the mass number of Zr is 91.2 and the mass number of Ta is 180.9, E1/E2 is preferably 0.15 or more and 1.51 or less, more preferably 0.25 or more and 1.01 or less.

[0118] In the case where the first element is Zr and the second element is V, since the mass number of Zr is 91.2 and the mass number of V is 50.9, E1/E2 is preferably 0.54 or more and 5.38 or less, more preferably 0.90 or more and 3.58 or less.

[0119] Also in the case of a combination other than the above-mentioned combinations, E1/E2 can be calculated in the same manner as described above.

[0120] Further, the presence of the high Si concentration region **4** can also be determined by, for example, a mapping analysis by energy dispersive X-ray spectrometry (EDX).

[0121] The content E1 of the first element and the content E2 of the second element are as described above, respectively, however, the sum of the contents of these elements is preferably 0.05% by mass or more and 0.6% by mass or less, more preferably 0.10% by mass or more and 0.48% by mass or less, further more preferably 0.12% by mass or more and 0.24% by mass or less. By setting the sum of the content of the first element and the content of the second element within the above range, the densification of a sintered body to be produced becomes necessary and sufficient.

[0122] When the ratio of the sum of the content of the first element and the content of the second element to the content of Si is represented by (E1+E2)/Si, (E1+E2)/Si is preferably 0.1 or more and 0.7 or less, more preferably 0.15 or more and 0.6 or less, further more preferably 0.2 or more and 0.5 or less in terms of mass ratio. By setting the ratio (E1+E2)/Si within the above range, a decrease in the toughness or the like when Si is added is sufficiently compensated by the addition of the first element and the second element. As a result, a metal powder capable of producing a sintered body which has excellent mechanical properties such as toughness in spite of having a high density and also has excellent corrosion resistance attributed to Si is obtained. In addition, in the particle **1**, necessary and sufficient accumulation of silicon oxide occurs by using the carbide or the like of the first element and the carbide or the like of the second element as nuclei, and in the case where an element such as Cr or Ni is contained in the particle **1** other than Fe, an oxidation reaction of such an element is easily suppressed. Therefore, also from this viewpoint, the sinterability of the particle **1** is enhanced, and thus, a sintered body having a higher density, excellent mechanical properties, and excellent corrosion resistance can be obtained.

[0123] With respect to the positional relationship between the carbide or the like of the first element or the carbide or the like of the second element and silicon oxide, it is not always necessary for the carbide or the like to be located at the center of silicon oxide, and for example, these components may have a positional relationship such that silicon oxide is accumulated inside the carbide or the like.

[0124] Further, when the ratio of the sum of the content of the first element and the content of the second element to the content of C is represented by (E1+E2)/C, (E1+E2)/C is preferably 1 or more and 16 or less, more preferably 2 or more and 13 or less, further more preferably 3 or more and 10 or less. By setting the ratio (E1+E2)/C within the above range, an increase in the hardness and the suppression of a decrease in the toughness when C is added, and an increase in the density brought about by the addition of the first element and the second element can be achieved. As a result, the particle **1** capable of producing a sintered body which has excellent mechanical properties such as tensile strength and toughness is obtained.

Another Element

[0125] The particle **1** may contain, other than the above-mentioned elements, at least one element of Mo, Pb, S, and Al as needed. These elements may be inevitably contained in some cases.

[0126] Mo is an element which enhances the corrosion resistance of a sintered body to be produced.

[0127] The content of Mo in the particle **1** is not particularly limited, but is preferably 0.2% by mass or more and 0.8% by mass or less, more preferably 0.3% by mass or more and 0.6% by mass or less. By setting the content of Mo within the above range, the corrosion resistance of a sintered body to be produced can be further enhanced without causing a large decrease in the density of the sintered body.

[0128] Pb is an element which enhances the machinability of a sintered body to be produced.

[0129] The content of Pb in the particle **1** is preferably 0.03% by mass or more and 0.5% by mass or less, more

preferably 0.05% by mass or more and 0.3% by mass or less. By setting the content of Pb within the above range, the machinability of a sintered body to be produced can be further enhanced.

[0130] S is an element which enhances the machinability of a sintered body to be produced.

[0131] The content of S in the particle **1** is not particularly limited, but is preferably 0.5% by mass or less, more preferably 0.01% by mass or more and 0.3% by mass or less. By setting the content of S within the above range, the machinability of a sintered body to be produced can be further enhanced without causing a large decrease in the density of the sintered body.

[0132] Al is an element which enhances the oxidation resistance of a sintered body to be produced.

[0133] The content of Al in the particle **1** is not particularly limited, but is preferably 0.5% by mass or less, more preferably 0.05% by mass or more and 0.3% by mass or less. By setting the content of Al within the above range, the oxidation resistance of a sintered body to be produced can be further enhanced without causing a large decrease in the density of the sintered body.

[0134] To the particle **1**, B, Se, Te, Pd, W, Co, N, Cu, or the like may be added other than the above-mentioned elements. At this time, the contents of these elements are not particularly limited, but the content of each of these elements is preferably less than 0.1% by mass, and also the total content of these elements is preferably less than 0.2% by mass. These elements may be inevitably contained in some cases.

[0135] The particle **1** may contain impurities. Examples of the impurities include all elements other than the above-mentioned elements, and specific examples thereof include Li, Be, Na, Mg, P, K, Ca, Sc, Zn, Ga, Ge, Ag, In, Sn, Sb, Os, Ir, Pt, Au, and Bi. The incorporation amounts of these impurity elements are preferably set such that the content of each of the impurity elements is less than the content of each of Fe, Cr, Si, the first element, and the second element. Further, the incorporation amounts of these impurity elements are preferably set such that the content of each of the impurity elements is less than 0.03% by mass, more preferably less than 0.02% by mass. Further, the total content of these impurity elements is set to preferably less than 0.3% by mass, more preferably less than 0.2% by mass. These elements do not inhibit the effect as described above as long as the contents thereof are within the above range, and therefore may be intentionally added to the metal powder.

[0136] Meanwhile, O (oxygen) may also be intentionally added to or inevitably mixed in the metal powder, however, the amount thereof is preferably about 0.8% by mass or less, more preferably about 0.5% by mass or less. By controlling the amount of oxygen in the particle **1** within the above range, the sinterability is enhanced, and thus, a sintered body having a high density and excellent mechanical properties is obtained. Incidentally, the lower limit thereof is not particularly set, but is preferably 0.03% by mass or more from the viewpoint of ease of mass production or the like.

[0137] Fe is a component (principal component) whose content is the highest in the alloy constituting the metal powder for powder metallurgy according to the invention and has a great influence on the properties of the sintered body. The content of Fe is not particularly limited, but is preferably 50% by mass or more.

[0138] The compositional ratio of the particle **1** can be determined by, for example, Iron and steel—Atomic absorption spectrometric method specified in JIS G 1257 (2000), Iron and steel—ICP atomic emission spectrometric method specified in JIS G 1258 (2007), Iron and steel—Method for spark discharge atomic emission spectrometric analysis specified in JIS G 1253 (2002), Iron and steel—Method for X-ray fluorescence spectrometric analysis specified in JIS G 1256 (1997), gravimetric, titrimetric, and absorption spectrometric methods specified in JIS G 1211 to G 1237, or the like. Specifically, for example, an optical emission spectrometer for solids (spark optical emission spectrometer, model: SPECTROLAB, type: LAVMB08A) manufactured by SPECTRO Analytical Instruments GmbH or an ICP device (model: CIROS-120) manufactured by Rigaku Corporation can be used.

[0139] Incidentally, the methods specified in JIS G 1211 to G 1237 are as follows.

[0140] JIS G 1211 (2011): Iron and steel—Methods for determination of carbon content

[0141] JIS G 1212 (1997): Iron and steel—Methods for determination of silicon content

[0142] JIS G 1213 (2001): Iron and steel—Methods for determination of manganese content

[0143] JIS G 1214 (1998): Iron and steel—Methods for determination of phosphorus content

[0144] JIS G 1215 (2010): Iron and steel—Methods for determination of sulfur content

[0145] JIS G 1216 (1997): Iron and steel—Methods for determination of nickel content

[0146] JIS G 1217 (2005): Iron and steel—Methods for determination of chromium content

[0147] JIS G 1218 (1999): Iron and steel—Methods for determination of molybdenum content

[0148] JIS G 1219 (1997): Iron and steel—Methods for determination of copper content

[0149] JIS G 1220 (1994): Iron and steel—Methods for determination of tungsten content

[0150] JIS G 1221 (1998): Iron and steel—Methods for determination of vanadium content

[0151] JIS G 1222 (1999): Iron and steel—Methods for determination of cobalt content

[0152] JIS G 1223 (1997): Iron and steel—Methods for determination of titanium content

[0153] JIS G 1224 (2001): Iron and steel—Methods for determination of aluminum content

[0154] JIS G 1225 (2006): Iron and steel—Methods for determination of arsenic content

[0155] JIS G 1226 (1994): Iron and steel—Methods for determination of tin content

[0156] JIS G 1227 (1999): Iron and steel—Methods for determination of boron content

[0157] JIS G 1228 (2006): Iron and steel—Methods for determination of nitrogen content

[0158] JIS G 1229 (1994): Steel—Methods for determination of lead content

[0159] JIS G 1232 (1980): Methods for determination of zirconium in steel

[0160] JIS G 1233 (1994): Steel—Method for determination of selenium content

[0161] JIS G 1234 (1981): Methods for determination of tellurium in steel

[0162] JIS G 1235 (1981): Methods for determination of antimony in iron and steel

[0163] JIS G 1236 (1992): Method for determination of tantalum in steel

[0164] JIS G 1237 (1997): Iron and steel—Methods for determination of niobium content

[0165] Further, when C (carbon) and S (sulfur) are determined, particularly, an infrared absorption method after combustion in a current of oxygen (after combustion in a high-frequency induction heating furnace) specified in JIS G 1211 (2011) is also used. Specifically, a carbon-sulfur analyzer, CS-200 manufactured by LECO Corporation can be used.

[0166] Further, when N (nitrogen) and O (oxygen) are determined, particularly, a method for determination of nitrogen content in iron and steel specified in JIS G 1228 (2006) and a method for determination of oxygen content in metallic materials specified in JIS Z 2613 (2006) are also used. Specifically, an oxygen-nitrogen analyzer, TC-300/EF-300 manufactured by LECO Corporation can be used.

[0167] The particle **1** as described above is preferably contained in the metal powder for powder metallurgy as much as possible, and specifically, the particle **1** is contained in the metal powder for powder metallurgy in an amount of preferably 50% by number or more, more preferably 60% by number or more. According to such a metal powder for powder metallurgy, the effect as described above is more reliably exhibited, and a sintered body having a high density and excellent mechanical properties can be more reliably produced.

[0168] The average particle diameter of the metal powder for powder metallurgy according to the invention is preferably 0.5 μm or more and 30 μm or less, more preferably 1 μm or more and 20 μm or less, further more preferably 2 μm or more and 10 μm or less. By using the metal powder for powder metallurgy having such a particle diameter, pores remaining in a sintered body are extremely reduced, and therefore, a sintered body having a particularly high density and particularly excellent mechanical properties can be produced.

[0169] The average particle diameter can be obtained as a particle diameter when the cumulative amount obtained by cumulating the percentages of the particles from the smaller diameter side reaches 50% in a cumulative particle size distribution on a mass basis obtained by laser diffractometry.

[0170] If the average particle diameter of the metal powder for powder metallurgy is less than the above lower limit, the moldability is deteriorated in the case where the shape is difficult to mold, and therefore, the sintered density may be decreased. On the other hand, if the average particle diameter of the metal powder exceeds the above upper limit, spaces between the particles become larger during molding, and therefore, the sintered density may be decreased also in this case.

[0171] The particle size distribution of the metal powder for powder metallurgy is preferably as narrow as possible. Specifically, when the average particle diameter of the metal powder for powder metallurgy is within the above range, the maximum particle diameter of the metal powder is preferably 200 μm or less, more preferably 150 μm or less. By controlling the maximum particle diameter of the metal powder for powder metallurgy within the above range, the particle size distribution of the metal powder for powder metallurgy can be made narrower, and thus, the density of the sintered body can be further increased.

[0172] Here, the "maximum particle diameter" refers to a particle diameter when the cumulative amount obtained by cumulating the percentages of the particles from the smaller diameter side reaches 99.9% in a cumulative particle size distribution on amass basis obtained by laser diffractometry.

[0173] When the minor axis of each particle of the metal powder for powder metallurgy is represented by S (μm) and the major axis thereof is represented by L (μm), the average of the aspect ratio defined by S/L is preferably about 0.4 or more and 1 or less, more preferably about 0.7 or more and 1 or less. The metal powder for powder metallurgy having an aspect ratio within this range has a shape relatively close to a spherical shape, and therefore, the packing factor when the metal powder is molded is increased. As a result, the density of the sintered body can be further increased.

[0174] Here, the "major axis" is the maximum length in the projected image of the particle, and the "minor axis" is the maximum length in the direction perpendicular to the major axis. Incidentally, the average of the aspect ratio can be obtained as the average of the measured aspect ratios of 100 or more particles.

[0175] The tap density of the metal powder for powder metallurgy according to the invention is preferably 3.5 g/cm^3 or more, more preferably 4 g/cm^3 or more. According to the metal powder for powder metallurgy having such a high tap density, when a molded body is obtained, the interparticle packing efficiency is particularly increased. Therefore, a particularly dense sintered body can be obtained in the end.

[0176] The specific surface area of the metal powder for powder metallurgy according to the invention is not particularly limited, but is preferably 0.1 m^2/g or more, more preferably 0.2 m^2/g or more. According to the metal powder for powder metallurgy having such a large specific surface area, a surface activity (surface energy) is increased so that it is possible to easily sinter the metal powder even if less energy is applied. Therefore, when a molded body is sintered, a difference in sintering rate hardly occurs between the inner side and the outer side of the molded body, and thus, the decrease in the sintered density due to the pores remaining inside the molded body can be suppressed.

Method for Producing Sintered Body

[0177] Next, a method for producing a sintered body using such a metal powder for powder metallurgy according to the invention will be described.

[0178] The method for producing a sintered body includes (A) a composition preparation step in which a composition for producing a sintered body is prepared, (B) a molding step in which a molded body is produced, (C) a degreasing step in which a degreasing treatment is performed, and (D) a firing step in which firing is performed. Hereinafter, the respective steps will be described sequentially.

(A) Composition Preparation Step

[0179] First, the metal powder for powder metallurgy according to the invention and a binder are prepared, and these materials are kneaded using a kneader, whereby a kneaded material (composition) is obtained.

[0180] In this kneaded material (an embodiment of the compound according to the invention), the metal powder for powder metallurgy is uniformly dispersed.

[0181] The metal powder for powder metallurgy according to the invention is produced by, for example, any of a variety of powdering methods such as an atomization method (such as a water atomization method, a gas atomization method, or

a spinning water atomization method), a reducing method, a carbonyl method, and a pulverization method.

[0182] Among these, the metal powder for powder metallurgy according to the invention is preferably a metal powder produced by an atomization method, more preferably a metal powder produced by a water atomization method or a spinning water atomization method. The atomization method is a method in which a molten metal (metal melt) is caused to collide with a fluid (liquid or gas) sprayed at a high speed to atomize the metal melt into a fine powder and also to cool the fine powder, whereby a metal powder is produced. By producing the metal powder for powder metallurgy through such an atomization method, an extremely fine powder can be efficiently produced. Further, the shape of the particle of the obtained powder is closer to a spherical shape by the action of surface tension. Due to this, when the metal powder is molded, a molded body having a high packing factor is obtained. That is, a powder capable of producing a sintered body having a high density can be obtained. In addition, the cooling rate of the metal melt is very high, and therefore, the particle **1** in which the sizes of the Fe-based alloy crystals **2** are uniform can be obtained.

[0183] In the case where a water atomization method is used as the atomization method, the pressure of water (hereinafter referred to as "atomization water") to be sprayed to the molten metal is not particularly limited, but is set to preferably about 75 MPa or more and 120 MPa or less (750 kgf/cm^2 or more and 1200 kgf/cm^2 or less), more preferably about 90 MPa or more and 120 MPa or less (900 kgf/cm^2 or more and 1200 kgf/cm^2 or less).

[0184] The temperature of the atomization water is also not particularly limited, but is preferably set to about 1° C. or higher and 20° C. or lower.

[0185] The atomization water is often sprayed in a cone shape such that it has a vertex on the falling path of the metal melt and the outer diameter gradually decreases downward. In this case, the vertex angle θ of the cone formed by the atomization water is preferably about 10° or more and 40° or less, more preferably about 15° or more and 35° or less. According to this, a metal powder for powder metallurgy having a composition as described above can be reliably produced.

[0186] Further, by using a water atomization method (particularly, a spinning water atomization method), the metal melt can be cooled particularly quickly. Due to this, a powder having high quality can be obtained in a wide alloy composition range.

[0187] The cooling rate when cooling the metal melt in the atomization method is preferably 1×10^{4}° C./s or more, more preferably 1×10^{5}° C./s or more. By the quick cooling in this manner, a homogeneous metal powder for powder metallurgy can be obtained. As a result, a sintered body having high quality can be obtained.

[0188] The thus obtained metal powder for powder metallurgy may be classified as needed. Examples of the classification method include dry classification such as sieving classification, inertial classification, and centrifugal classification, and wet classification such as sedimentation classification.

[0189] Examples of the binder include polyolefins such as polyethylene, polypropylene, and ethylene-vinyl acetate copolymers, acrylic resins such as polymethyl methacrylate and polybutyl methacrylate, styrenic resins such as polystyrene, polyesters such as polyvinyl chloride, polyvinylidene chloride, polyamide, polyethylene terephthalate, and polybutylene terephthalate, various resins such as polyether, polyvinyl alcohol, polyvinylpyrrolidone, and copolymers thereof, and various organic binders such as various waxes, paraffins, higher fatty acids (such as stearic acid), higher alcohols, higher fatty acid esters, and higher fatty acid amides. These can be used alone or by mixing two or more types thereof.

[0190] The content of the binder is preferably about 2% by mass or more and 20% by mass or less, more preferably about 5% by mass or more and 10% by mass or less with respect to the total amount of the kneaded material. By setting the content of the binder within the above range, a molded body can be formed with good moldability, and also the density is increased, whereby the stability of the shape of the molded body and the like can be particularly enhanced. Further, according to this, a difference in size between the molded body and the degreased body, that is, so-called a shrinkage ratio is optimized, whereby a decrease in the dimensional accuracy of the finally obtained sintered body can be prevented. That is, a sintered body having a high density and high dimensional accuracy can be obtained.

[0191] In the kneaded material, a plasticizer may be added as needed. Examples of the plasticizer include phthalate esters (such as DOP, DEP, and DBP), adipate esters, trimellitate esters, and sebacate esters. These can be used alone or by mixing two or more types thereof.

[0192] Further, in the kneaded material, other than the metal powder for powder metallurgy, the binder, and the plasticizer, for example, any of a variety of additives such as a lubricant, an antioxidant, a degreasing accelerator, and a surfactant can be added as needed.

[0193] The kneading conditions vary depending on the respective conditions such as the metal composition or the particle diameter of the metal powder for powder metallurgy to be used, the composition of the binder, and the blending amount thereof. However, for example, the kneading temperature can be set to about 50° C. or higher and 200° C. or lower, and the kneading time can be set to about 15 minutes or more and 210 minutes or less.

[0194] Further, the kneaded material is formed into a pellet (small particle) as needed. The particle diameter of the pellet is set to, for example, about 1 mm or more and 15 mm or less.

[0195] Incidentally, depending on the molding method described below, in place of the kneaded material, a granulated powder may be produced. The kneaded material, the granulated powder, and the like are examples of the composition to be subjected to the molding step described below.

[0196] The embodiment of the granulated powder according to the invention is directed to a granulated powder obtained by binding a plurality of metal particles to one another with a binder by subjecting the metal powder for powder metallurgy according to the invention to a granulation treatment.

[0197] Examples of the binder to be used for producing the granulated powder include polyolefins such as polyethylene, polypropylene, and ethylene-vinyl acetate copolymers, acrylic resins such as polymethyl methacrylate and polybutyl methacrylate, styrenic resins such as polystyrene, polyesters such as polyvinyl chloride, polyvinylidene chloride, polyamide, polyethylene terephthalate, and polybutylene terephthalate, various resins such as polyether, polyvinyl alcohol, polyvinylpyrrolidone, and copolymers thereof, and various organic binders such as various waxes, paraffins, higher fatty acids (such as stearic acid), higher alcohols, higher fatty acid

esters, and higher fatty acid amides. These can be used alone or by mixing two or more types thereof.

[0198] Among these, as the binder, a binder containing a polyvinyl alcohol or polyvinylpyrrolidone is preferred. These binder components have a high binding ability, and therefore can efficiently form the granulated powder even in a relatively small amount. Further, the thermal decomposability thereof is also high, and therefore, the binder can be reliably decomposed and removed in a short time during degreasing and firing.

[0199] The content of the binder is preferably about 0.2% by mass or more and 10% by mass or less, more preferably about 0.3% by mass or more and 5% by mass or less, further more preferably about 0.3% by mass or more and 2% by mass or less with respect to the total amount of the granulated powder. By setting the content of the binder within the above range, the granulated powder can be efficiently formed while preventing significantly large particles from being formed or the metal particles which are not granulated from remaining in a large amount. Further, since the moldability is improved, the stability of the shape of the molded body and the like can be particularly enhanced. Further, by setting the content of the binder within the above range, a difference in size between the molded body and the degreased body, that is, so-called a shrinkage ratio is optimized, whereby a decrease in the dimensional accuracy of the finally obtained sintered body can be prevented.

[0200] Further, in the granulated powder, any of a variety of additives such as a plasticizer, a lubricant, an antioxidant, a degreasing accelerator, and a surfactant may be added as needed.

[0201] Examples of the granulation treatment include a spray drying method, a tumbling granulation method, a fluidized bed granulation method, and a tumbling fluidized bed granulation method.

[0202] In the granulation treatment, a solvent which dissolves the binder is used as needed. Examples of the solvent include inorganic solvents such as water and carbon tetrachloride, and organic solvents such as ketone-based solvents, alcohol-based solvents, ether-based solvents, cellosolve-based solvents, aliphatic hydrocarbon-based solvents, aromatic hydrocarbon-based solvents, aromatic heterocyclic compound-based solvents, amide-based solvents, halogen compound-based solvents, ester-based solvents, amine-based solvents, nitrile-based solvents, nitro-based solvents, and aldehyde-based solvents, and one type or a mixture of two or more types selected from these solvents is used.

[0203] The average particle diameter of the granulated powder is not particularly limited, but is preferably about 10 μm or more and 200 μm or less, more preferably about 20 μm or more and 100 μm or less, further more preferably about 25 μm or more and 60 μm or less. The granulated powder having such a particle diameter has favorable fluidity, and can more faithfully reflect the shape of a molding die.

[0204] The average particle diameter can be obtained as a particle diameter when the cumulative amount obtained by cumulating the percentages of the particles from the smaller diameter side reaches 50% in a cumulative particle size distribution on amass basis obtained by laser diffractometry.

(B) Molding Step

[0205] Subsequently, the kneaded material or the granulated powder is molded, whereby a molded body having the same shape as that of a target sintered body is produced.

[0206] The method for producing a molded body (molding method) is not particularly limited, and for example, any of a variety of molding methods such as a powder compacting (compression molding) method, a metal injection molding (MIM) method, and an extrusion molding method can be used.

[0207] The molding conditions in the case of a powder compacting method among these methods are preferably such that the molding pressure is about 200 MPa or more and 1000 MPa or less (2 t/cm^2 or more and 10 t/cm^2 or less), which vary depending on the respective conditions such as the composition and the particle diameter of the metal powder for powder metallurgy to be used, the composition of the binder, and the blending amount thereof.

[0208] The molding conditions in the case of a metal injection molding method are preferably such that the material temperature is about 80° C. or higher and 210° C. or lower, and the injection pressure is about 50 MPa or more and 500 MPa or less (0.5 t/cm^2 or more and 5 t/cm^2 or less), which vary depending on the respective conditions.

[0209] The molding conditions in the case of an extrusion molding method are preferably such that the material temperature is about 80° C. or higher and 210° C. or lower, and the extrusion pressure is about 50 MPa or more and 500 MPa or less (0.5 t/cm^2 or more and 5 t/cm^2 or less), which vary depending on the respective conditions.

[0210] The thus obtained molded body is in a state where the binder is uniformly distributed in spaces between the particles of the metal powder.

[0211] The shape and size of the molded body to be produced are determined in anticipation of shrinkage of the molded body in the subsequent degreasing step and firing step.

(C) Degreasing Step

[0212] Subsequently, the thus obtained molded body is subjected to a degreasing treatment (binder removal treatment), whereby a degreased body is obtained.

[0213] Specifically, the binder is decomposed by heating the molded body, whereby the binder is removed from the molded body. In this manner, the degreasing treatment is performed.

[0214] Examples of the degreasing treatment include a method of heating the molded body and a method of exposing the molded body to a gas capable of decomposing the binder.

[0215] In the case of using a method of heating the molded body, the conditions for heating the molded body are preferably such that the temperature is about 100° C. or higher and 750° C. or lower and the time is about 0.1 hours or more and 20 hours or less, and more preferably such that the temperature is about 150° C. or higher and 600° C. or lower and the time is about 0.5 hours or more and 15 hours or less, which slightly vary depending on the composition and the blending amount of the binder. According to this, the degreasing of the molded body can be necessarily and sufficiently performed without sintering the molded body. As a result, it is possible to reliably prevent the binder component from remaining inside the degreased body in a large amount.

[0216] The atmosphere when the molded body is heated is not particularly limited, and an atmosphere of a reducing gas such as hydrogen, an atmosphere of an inert gas such as nitrogen or argon, an atmosphere of an oxidative gas such as air, a reduced pressure atmosphere obtained by reducing the pressure of such an atmosphere, or the like can be used.

[0217] Examples of the gas capable of decomposing the binder include ozone gas.

[0218] Incidentally, by dividing this degreasing step into a plurality of steps in which the degreasing conditions are different, and performing the plurality of steps, the binder in the molded body can be more rapidly decomposed and removed so that the binder does not remain in the molded body.

[0219] Further, according to need, the degreased body may be subjected to a machining process such as grinding, polishing, or cutting. The degreased body has a relatively low hardness and relatively high plasticity, and therefore, the machining process can be easily performed while preventing the degreased body from losing its shape. According to such a machining process, a sintered body having high dimensional accuracy can be easily obtained in the end.

(D) Firing Step

[0220] The degreased body obtained in the above step (C) is fired in a firing furnace, whereby a sintered body is obtained.

[0221] By this firing, in the metal powder for powder metallurgy, diffusion occurs at the boundary surface between the particles, resulting in sintering. At this time, by the mechanism as described above, the degreased body is rapidly sintered. As a result, a sintered body which is dense and has a high density on the whole is obtained.

[0222] The firing temperature varies depending on the composition, the particle diameter, and the like of the metal powder for powder metallurgy used in the production of the molded body and the degreased body, but is set to, for example, about 980° C. or higher and 1330° C. or lower, and preferably set to about 1050° C. or higher and 1260° C. or lower.

[0223] Further, the firing time is set to 0.2 hours or more and 7 hours or less, but is preferably set to about 1 hour or more and 6 hours or less.

[0224] In the firing step, the firing temperature or the below-described firing atmosphere may be changed in the middle of the step.

[0225] By setting the firing conditions within such a range, it is possible to sufficiently sinter the entire degreased body while preventing the sintering from proceeding excessively to cause oversintering and increase the size of the crystal structure. As a result, a sintered body having a high density and particularly excellent mechanical properties can be obtained.

[0226] Further, since the firing temperature is a relatively low temperature, it is easy to control the heating temperature in the firing furnace to be a fixed temperature, and therefore, it is also easy to maintain the temperature of the degreased body at a fixed temperature. As a result, a more homogeneous sintered body can be produced.

[0227] Further, since the firing temperature as described above is a temperature which can be sufficiently realized using a common firing furnace, and therefore, an inexpensive firing furnace can be used, and also the running cost can be kept low. In other words, in the case where the temperature exceeds the above-mentioned firing temperature, it is necessary to employ an expensive firing furnace using a special heat resistant material, and also the running cost may be increased.

[0228] The atmosphere when performing firing is not particularly limited, however, in consideration of prevention of significant oxidation of the metal powder, an atmosphere of a reducing gas such as hydrogen, an atmosphere of an inert gas such as argon, a reduced pressure atmosphere obtained by reducing the pressure of such an atmosphere, or the like is preferably used.

[0229] The thus obtained sintered body has a high density and excellent mechanical properties. That is, a sintered body produced by molding a composition containing the metal powder for powder metallurgy according to the invention and a binder, followed by degreasing and sintering has a higher relative density than a sintered body obtained by sintering a metal powder in the related art. Therefore, according to the invention, a sintered body having a high density which could not be obtained unless an additional treatment such as an HIP treatment is performed can be realized without performing an additional treatment.

[0230] Specifically, according to the invention, for example, the relative density can be expected to be increased by 2% or more as compared with the related art, which slightly varies depending on the composition of the metal powder for powder metallurgy.

[0231] As a result, the relative density of the obtained sintered body can be expected to be, for example, 97% or more (preferably 98% or more, more preferably 98.5% or more). The sintered body having a relative density within such a range has excellent mechanical properties comparable to those of ingot materials although it has a shape as close as possible to a desired shape by using a powder metallurgy technique, and therefore, the sintered body can be applied to a variety of machine parts, structural parts, and the like with virtually no post-processing.

[0232] Further, the tensile strength and the 0.2% proof stress of a sintered body produced by molding a composition containing the metal powder for powder metallurgy according to the invention and a binder, followed by degreasing and sintering are higher than those of a sintered body obtained by performing sintering in the same manner using a metal powder in the related art. This is considered to be because by optimizing the alloy composition and the crystal structure of the particle, the sinterability of the metal powder is enhanced, and thus, the mechanical properties of a sintered body to be produced using the metal powder are enhanced.

[0233] Further, the sintered body produced as described above has a high surface hardness. Specifically, as one example, the Vickers hardness of the surface of the sintered body is expected to be 570 or more and 1200 or less, which slightly varies depending on the composition of the metal powder for powder metallurgy, and further is expected to be preferably 600 or more and 1000 or less. The sintered body having such a hardness has particularly high durability.

[0234] The sintered body has a sufficiently high density and excellent mechanical properties even without performing an additional treatment, however, in order to further increase the density and enhance the mechanical properties, a variety of additional treatments may be performed.

[0235] As the additional treatment, for example, an additional treatment of increasing the density such as the HIP treatment described above may be performed, and also a variety of quenching treatments, a variety of sub-zero treatments, a variety of tempering treatments, and the like may be performed. These additional treatments may be performed alone or two or more treatments thereof may be performed in combination.

[0236] Among these treatments, in the quenching treatment, after the sintered body is heated to about 980° C. or higher and 1200° C. or lower for about 0.2 hours or more and

3 hours or less, a rapid cooling treatment is performed. By doing this, an austenite crystal structure can be transformed into a martensite crystal structure, which varies also depending on the composition of the metal powder for powder metallurgy. Accordingly, this treatment is preferably used, for example, when a sintered body containing a martensite crystal structure is produced.

[0237] For the rapid cooling in the quenching treatment, water cooling, oil cooling, or the like is used.

[0238] Further, the sub-zero treatment is a treatment in which an austenite crystal structure which is not transformed into a martensite crystal structure by the quenching treatment and is retained is transformed into martensite by cooling. The retained austenite crystal structure is often transformed into martensite over time, however, at this time, the volume of the sintered body changes. Therefore, a problem occurs that the size of the sintered body changes over time. Therefore, by performing the sub-zero treatment after the quenching treatment, the retained austenite crystal structure can be transformed into martensite partly forcibly, and thus, the occurrence of the problem that the size changes over time can be prevented.

[0239] In the cooling of the sintered body, for example, dry ice, carbon dioxide gas, liquid nitrogen, or the like is used.

[0240] In the sub-zero treatment, it is preferred that the temperature is about 0° C. or lower and the time is about 0.2 hours or more and 3 hours or less.

[0241] Further, the tempering treatment is a treatment in which the sintered body having undergone the quenching treatment is heated again at a lower temperature than in the quenching treatment. By doing this, toughness can be provided while decreasing the hardness of the sintered body.

[0242] In the tempering treatment, it is preferred that the temperature is about 100° C. or higher and 200° C. or lower and the time is about 0.3 hours or more and 5 hours or less.

[0243] In the firing step and a variety of additional treatments described above, a light element in the metal powder (in the sintered body) is volatilized, and the composition of the finally obtained sintered body slightly changes from the composition of the metal powder in some cases.

[0244] For example, the content of C in the final sintered body may change within the range of 5% or more and 100% or less (preferably within the range of 30% or more and 100% or less) of the content of C in the metal powder for powder metallurgy, which varies depending on the conditions for the step or the conditions for the treatment.

[0245] Also the content of O in the final sintered body may change within the range of 1% or more and 50% or less (preferably within the range of 3% or more and 50% or less) of the content of O in the metal powder for powder metallurgy, which varies depending on the conditions for the step or the conditions for the treatment.

[0246] On the other hand, as described above, the produced sintered body may be subjected to an HIP treatment as part of the additional treatments to be performed as needed, however, even if the HIP treatment is performed, a sufficient effect is not exhibited in many cases. In the HIP treatment, the density of the sintered body can be further increased, however, in the first place, the density of the sintered body obtained according to the invention has already been sufficiently increased at the end of the firing step. Therefore, even if the HIP treatment is further performed, densification hardly proceeds any further.

[0247] In addition, in the HIP treatment, it is necessary to apply pressure to a material to be treated through a pressure medium, and therefore, the material to be treated may be contaminated, the composition or the physical properties of the material to be treated may unintentionally change accompanying the contamination, or the color of the material to be treated may change accompanying the contamination. Further, by the application of pressure, residual stress is generated or increased in the material to be treated, and a problem such as a change in the shape or a decrease in the dimensional accuracy may occur as the residual stress is released over time.

[0248] On the other hand, according to the invention, a sintered body having a sufficiently high density can be produced without performing such an HIP treatment, and therefore, a sintered body having an increased density and also an increased strength can be obtained in the same manner as in the case of performing an HIP treatment. Such a sintered body is less contaminated and discolored, and also an unintended change in the composition or physical properties, or the like occurs less, and also a problem such as a change in the shape or a decrease in the dimensional accuracy occurs less. Therefore, according to the invention, a sintered body having high mechanical strength and dimensional accuracy, and excellent durability can be efficiently produced.

[0249] Further, the sintered body produced according to the invention requires almost no additional treatments for enhancing the mechanical properties, and therefore, the composition and the crystal structure tend to become uniform in the entire sintered body. Due to this, the sintered body has high structural anisotropy and therefore has excellent durability against a load from every direction regardless of its shape.

[0250] Incidentally, it is confirmed that in the thus produced sintered body, the porosity near the surface thereof is often relatively lower than inside the sintered body. The reason therefor is not clear, however, one of the reasons is that by the addition of the first element and the second element, the sintering reaction more easily proceeds near the surface of the molded body than inside the molded body.

[0251] Specifically, when the porosity near the surface of the sintered body is represented by A1 and the porosity inside the sintered body is represented by A2, A2-A1 is preferably 0.1% or more and 3% or less, more preferably 0.2% or more and 2% or less. The sintered body showing the value of A2-A1 within the above range not only has necessary and sufficient mechanical strength, but also can easily flatten the surface. That is, by polishing the surface of such a sintered body, a surface having high specularity can be obtained.

[0252] Such a sintered body having high specularity not only has high mechanical strength, but also has excellent aesthetic properties. Therefore, such a sintered body is favorably used also for application requiring excellent aesthetic appearance.

[0253] Incidentally, the porosity A1 near the surface of the sintered body refers to a porosity in a 25-μm radius region centered on the position at a depth of 50 μm from the surface of the cross section of the sintered body. Further, the porosity A2 inside the sintered body refers to a porosity in a 25-pt radius region centered on the position at a depth of 300 μm from the surface of the cross section of the sintered body. These porosities are values obtained by observing the cross section of the sintered body with a scanning electron microscope and dividing the area of pores present in the region by the area of the region.

[0254] Hereinabove, the metal powder for powder metallurgy, the compound, the granulated powder, and the sintered body according to the invention have been described with reference to preferred embodiments, however, the invention is not limited thereto.

[0255] Further, the sintered body according to the invention is used for, for example, parts for transport machinery such as parts for automobiles, parts for bicycles, parts for railroad cars, parts for ships, parts for airplanes, and parts for space transport machinery (such as rockets); parts for electronic devices such as parts for personal computers and parts for mobile phone terminals; parts for electrical devices such as

refrigerators, washing machines, and cooling and heating machines; parts for machines such as machine tools and semiconductor production devices; parts for plants such as atomic power plants, thermal power plants, hydroelectric power plants, oil refinery plants, and chemical complexes; parts for timepieces, metallic tableware, jewels, ornaments such as frames for glasses, and all other sorts of structural parts.

EXAMPLES

[0256] Next, Examples of the invention will be described.

1. Production of Sintered Body (Zr—Nb Based)

Sample No. 1

[0257] (1) First, a metal powder having a composition shown in Table 1 produced by a water atomization method was prepared.

[0258] The composition of the powder shown in Table 1 was identified and quantitatively determined by an inductively coupled high-frequency plasma optical emission spectrometry (ICP analysis method). In the ICP analysis, an ICP device (model: CIROS-120) manufactured by Rigaku Corporation was used. Further, in the identification and determination of C, a carbon-sulfur analyzer (CS-200) manufactured by LECO Corporation was used. Further, in the identification and determination of O, an oxygen-nitrogen analyzer (TC-300/EF-300) manufactured by LECO Corporation was used.

[0259] (2) Subsequently, the metal powder and a mixture (organic binder) of polypropylene and a wax were weighed at a mass ratio of 9:1 and mixed with each other, whereby a mixed starting material was obtained.

[0260] (3) Subsequently, this mixed starting material was kneaded using a kneader, whereby a compound was obtained.

[0261] (4) Subsequently, this compound was molded using an injection molding device under the following molding conditions, whereby a molded body was produced.

[0262] Molding Conditions

[0263] Material temperature: 150° C.

[0264] Injection pressure: 11 MPa (110 kgf/cm^2)

[0265] (5) Subsequently, the obtained molded body was subjected to a heat treatment (degreasing treatment) under the following degreasing conditions, whereby a degreased body was obtained.

[0266] Degreasing Conditions

[0267] Degreasing temperature: 500° C.

[0268] Degreasing time: 1 hour (retention time at the degreasing temperature)

[0269] Degreasing atmosphere: nitrogen atmosphere

[0270] (6) Subsequently, the obtained degreased body was fired under the following firing conditions, whereby a sintered body was obtained. The shape of the sintered body was determined to be a cylinder with a diameter of 10 mm and a thickness of 5 mm.

[0271] Firing Conditions

[0272] Firing temperature: 1200° C.

[0273] Firing time: 3 hours (retention time at the firing temperature)

[0274] Firing atmosphere: argon atmosphere

[0275] (7) Subsequently, the obtained sintered body was subjected to a quenching treatment under the following conditions.

[0276] Quenching Treatment Conditions

[0277] Quenching temperature: 980° C.

[0278] Quenching time: 4 hours

[0279] Quenching atmosphere: argon atmosphere

[0280] Cooling method: water cooling

[0281] (8) Subsequently, the sintered body having undergone the quenching treatment was subjected to a sub-zero treatment under the following conditions.

[0282] Sub-Zero Treatment Conditions

[0283] Sub-zero treatment temperature: −196° C.

[0284] Sub-zero treatment time: 2 hours

[0285] (9) Subsequently, the sintered body having undergone the sub-zero treatment was subjected to a tempering treatment under the following conditions.

[0286] Tempering Treatment Conditions

[0287] Tempering treatment temperature: 210° C.

[0288] Tempering treatment time: 4 hours

Sample Nos. 2 to 67

[0289] Sintered bodies were obtained in the same manner as the method for producing the sintered body of sample No. 1 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 1 or 2, respectively. The sintered bodies of sample Nos. 36 and 67 were obtained by performing an HIP treatment under the following conditions after firing. Further, the sintered bodies of sample Nos. 28 to 30 and 57 to 59 were obtained by using the metal powder produced by a gas atomization method, respectively, and indicated by "gas" in the column of Remarks in Tables 1 and 2.

[0290] HIP Treatment Conditions

[0291] Heating temperature: 1100° C.

[0292] Heating time: 2 hours

[0293] Applied pressure: 100 MPa

TABLE 1

		Metal powder for powder metallurgy																
		Alloy composition																
Sample No.	—	Cr	C	Si	E1 (Zr)	E2 (Nb)	Mn	Ni	Cu	O	Fe	E1/E2 —	E1 + E2 mass %	(E2)/Si —	(E2)/C —	(E1 + Mn + Ni) mass %	Remarks —
		mass %																
No. 1	Example	12.88	0.90	0.73	0.07	0.07	0.10	0.07	<0.01	0.27	remainder	1.00	0.14	0.19	0.16	0.17		
No. 2	Example	14.24	0.28	0.58	0.09	0.05	0.12	0.05	<0.01	0.24	remainder	1.80	0.14	0.24	0.50	0.17		
No. 3	Example	11.63	1.13	0.78	0.05	0.06	0.07	0.05	<0.01	0.31	remainder	0.83	0.11	0.14	0.10	0.12		
No. 4	Example	13.37	0.85	0.64	0.10	0.05	0.08	0.10	<0.01	0.25	remainder	2.00	0.15	0.23	0.18	0.18		
No. 5	Example	12.54	0.98	0.75	0.05	0.10	0.11	0.06	<0.01	0.29	remainder	0.50	0.15	0.20	0.15	0.17		
No. 6	Example	11.23	0.47	0.52	0.12	0.04	0.12	0.12	<0.01	0.22	remainder	3.00	0.16	0.31	0.34	0.24		
No. 7	Example	14.87	0.98	0.69	0.04	0.12	0.09	0.05	<0.01	0.41	remainder	0.33	0.16	0.23	0.16	0.14		
No. 8	Example	12.64	0.74	0.77	0.11	0.09	0.08	0.08	<0.01	0.30	remainder	1.22	0.20	0.26	0.27	0.16		
No. 9	Example	13.89	0.65	0.51	0.05	0.05	0.11	0.05	<0.01	0.28	remainder	1.00	0.10	0.20	0.15	0.16		
No. 10	Example	10.56	0.78	0.32	0.08	0.09	0.18	0.15	<0.01	0.25	remainder	0.89	0.17	0.53	0.22	0.33		
No. 11	Example	16.26	1.05	0.62	0.08	0.06	0.05	0.07	<0.01	0.29	remainder	1.33	0.14	0.23	0.13	0.12		
No. 12	Example	19.74	0.92	0.88	0.10	0.10	0.04	0.08	<0.01	0.48	remainder	1.00	0.20	0.23	0.22	0.12		

TABLE 1-continued

		Metal powder for powder metallurgy																
		Alloy composition													(E1 +	(E1 +		
Sample No.	—	Cr	C	Si	E1 (Zr)	E2 (Nb)	Mn	Ni	Cu	O	Fe	E1/ E2	E1 + E2	E2)/ Si	E2)/ C	Mn + Ni	Re- marks
		mass %										—	mass %	—	—	mass %	—
No. 13	Example	23.69	0.41	0.44	0.08	0.08	0.07	0.06	<0.01	0.68	remainder	1.00	0.16	0.36	0.39	0.13	
No. 14	Example	10.20	0.55	0.65	0.14	0.04	0.09	0.06	<0.01	0.19	remainder	3.50	0.18	0.28	0.33	0.15	
No. 15	Example	12.91	0.81	0.68	0.03	0.14	0.07	0.07	<0.01	0.27	remainder	0.21	0.17	0.25	0.21	0.14	
No. 16	Example	11.89	0.88	0.75	0.05	0.03	0.09	0.07	<0.01	0.23	remainder	1.67	0.08	0.11	0.09	0.16	
No. 17	Example	12.78	0.74	0.61	0.12	0.12	0.11	0.06	<0.01	0.25	remainder	1.00	0.24	0.39	0.32	0.17	
No. 18	Example	12.80	0.87	0.75	0.07	0.08	0.01	0.06	<0.01	0.24	remainder	0.88	0.15	0.20	0.17	0.07	gas
No. 19	Example	12.80	0.87	0.75	0.07	0.08	0.30	0.05	<0.01	0.24	remainder	0.88	0.15	0.20	0.17	0.35	gas
No. 20	Example	12.80	0.87	0.75	0.07	0.08	1.00	0.60	<0.01	0.24	remainder	0.88	0.15	0.20	0.17	1.60	gas
No. 21	Example	12.88	0.90	0.73	0.07	0.07	0.10	0.20	<0.01	0.27	remainder	1.00	0.14	0.19	0.16	0.30	
No. 22	Example	12.75	0.93	0.71	0.01	0.07	0.11	0.07	<0.01	0.29	remainder	0.14	0.08	0.11	0.09	0.18	
No. 23	Example	12.94	1.02	0.79	0.05	0.01	0.09	0.06	<0.01	0.31	remainder	5.00	0.06	0.08	0.06	0.15	
No. 24	Example	11.56	0.63	0.54	0.21	0.07	0.11	0.08	<0.01	0.38	remainder	3.00	0.28	0.52	0.44	0.19	
No. 25	Example	14.35	0.47	0.77	0.06	0.19	0.05	0.04	<0.01	0.41	remainder	0.32	0.25	0.32	0.53	0.09	
No. 26	Example	12.11	0.51	0.53	0.20	0.17	0.11	0.08	<0.01	0.27	remainder	1.18	0.37	0.70	0.73	0.19	
No. 27	Example	12.78	0.78	0.72	0.32	0.41	0.12	0.08	<0.01	0.31	remainder	0.78	0.73	1.01	0.94	0.20	
No. 28	Example	13.37	0.85	0.64	0.10	0.05	0.08	0.10	<0.01	0.25	remainder	2.00	0.15	0.23	0.18	0.18	gas
No. 29	Example	12.54	0.98	0.75	0.05	0.10	0.11	0.06	<0.01	0.29	remainder	0.50	0.15	0.10	0.15	0.17	gas
No. 30	Example	11.23	0.47	0.52	0.12	0.04	0.12	0.12	<0.01	0.22	remainder	3.00	0.16	0.31	0.34	0.24	gas
No. 31	Comparative Example	12.54	0.95	0.82	0.00	0.05	0.12	0.08	<0.01	0.25	remainder	0.00	0.05	0.06	0.05	0.20	
No. 32	Comparative Example	12.95	0.76	0.78	0.04	0.00	0.08	0.10	<0.01	0.31	remainder	—	0.04	0.05	0.05	0.18	
No. 33	Comparative Example	13.25	0.45	0.42	0.68	0.05	0.08	0.06	<0.01	0.27	remainder	13.60	0.73	1.74	1.62	0.14	
No. 34	Comparative Example	13.58	0.58	0.36	0.03	0.62	0.07	0.05	<0.01	0.32	remainder	0.05	0.65	1.81	1.12	0.12	
No. 35	Comparative Example	13.50	1.00	0.75	0.00	0.00	0.12	0.11	<0.01	0.33	remainder	—	0.00	0.00	0.00	0.23	
No. 36	Comparative Example	13.50	1.00	0.75	0.00	0.00	0.12	0.11	<0.01	0.33	remainder	—	0.00	0.00	0.00	0.23	HIP

TABLE 2

		Metal powder for powder metallurgy																
		Alloy composition													(E1 +	(E1 +		
Sample No.	—	Cr	C	Si	E1 (Zr)	E2 (Nb)	Mn	Ni	Cu	O	Fe	E1/ E2	E1 + E2	E2)/ Si	E2)/ C	Mn + Ni	Re- marks
		mass %										—	mass %	—	—	mass %	—
No. 37	Example	17.00	1.00	0.80	0.07	0.07	0.10	0.20	<0.01	0.27	remainder	1.00	0.14	0.18	0.14	0.30	
No. 38	Example	16.78	0.98	0.58	0.09	0.05	0.12	0.25	<0.01	0.24	remainder	1.80	0.14	0.24	0.14	0.37	
No. 39	Example	17.69	1.05	0.78	0.05	0.06	0.07	0.05	<0.01	0.31	remainder	0.83	0.11	0.14	0.10	0.12	
No. 40	Example	16.23	1.04	0.52	0.12	0.04	0.09	0.15	<0.01	0.22	remainder	3.00	0.16	0.31	0.15	0.24	
No. 41	Example	16.87	1.09	0.69	0.04	0.12	0.09	0.05	<0.01	0.41	remainder	0.33	0.16	0.23	0.15	0.14	
No. 42	Example	17.64	0.68	0.77	0.11	0.09	0.08	0.08	<0.01	0.30	remainder	1.22	0.20	0.26	0.29	0.16	
No. 43	Example	17.89	0.72	0.51	0.05	0.05	0.11	0.05	<0.01	0.28	remainder	1.00	0.10	0.20	0.14	0.16	
No. 44	Example	16.50	1.12	0.32	0.08	0.09	0.18	0.15	<0.01	0.25	remainder	0.89	0.17	0.53	0.15	0.33	
No. 45	Example	16.26	1.05	0.62	0.08	0.06	0.05	0.07	<0.01	0.29	remainder	1.33	0.14	0.23	0.13	0.12	
No. 46	Example	17.74	0.96	0.88	0.10	0.10	0.04	0.08	<0.01	0.48	remainder	1.00	0.20	0.23	0.21	0.12	
No. 47	Example	16.69	0.98	0.44	0.08	0.08	0.07	0.09	<0.01	0.57	remainder	1.00	0.16	0.36	0.16	0.16	
No. 48	Example	17.81	0.96	0.75	0.07	0.08	0.01	0.06	<0.01	0.24	remainder	0.88	0.15	0.20	0.16	0.07	
No. 49	Example	16.56	0.78	0.84	0.07	0.08	1.00	0.60	<0.01	0.24	remainder	0.88	0.15	0.18	0.19	1.60	
No. 50	Example	17.56	0.95	0.81	0.01	0.07	0.12	0.08	<0.01	0.31	remainder	0.14	0.08	0.10	0.08	0.20	
No. 51	Example	16.94	1.06	0.89	0.05	0.01	0.10	0.07	<0.01	0.29	remainder	5.00	0.06	0.07	0.06	0.17	
No. 52	Example	17.56	0.78	0.54	0.21	0.07	0.11	0.08	<0.01	0.38	remainder	3.00	0.28	0.52	0.36	0.19	
No. 53	Example	16.35	0.76	0.77	0.06	0.19	0.05	0.04	<0.01	0.41	remainder	0.32	0.25	0.32	0.33	0.09	
No. 54	Example	17.78	0.99	0.72	0.41	0.35	0.13	0.09	<0.01	0.31	remainder	1.17	0.76	1.06	0.77	0.22	
No. 55	Example	13.25	0.18	0.79	0.07	0.07	0.15	0.21	<0.01	0.25	remainder	1.00	0.14	0.18	0.78	0.36	

TABLE 2-continued

		Metal powder for powder metallurgy																
		Alloy composition													(E1 +	(E1 +		
Sample No.	—	Cr	C	Si	E1 (Zr)	E2 (Nb)	Mn	Ni	Cu	O	Fe	E1/ E2	E1 + E2	E2)/ Si	E2)/ C	Mn + Ni	Re- marks
		mass %										—	mass %	—	—	mass %	—
No. 56	Example	13.02	0.36	0.81	0.08	0.06	0.08	0.19	<0.01	0.19	remainder	1.33	0.14	0.17	0.39	0.27	
No. 57	Example	17.00	1.00	0.80	0.07	0.07	0.10	0.20	<0.01	0.27	remainder	1.00	0.14	1.18	0.14	0.30	gas
No. 58	Example	16.78	0.98	0.58	0.09	0.05	0.12	0.25	<0.01	0.24	remainder	1.80	0.14	0.24	0.14	0.37	gas
No. 59	Example	17.69	1.05	0.78	0.05	0.06	0.07	0.05	<0.01	0.31	remainder	0.83	0.11	0.14	0.10	0.12	gas
No. 60	Compar- ative Example	17.54	0.99	0.82	0.00	0.06	0.11	0.09	<0.01	0.29	remainder	0.00	0.06	0.07	0.06	0.20	
No. 61	Compar- ative Example	16.95	1.05	0.78	0.07	0.00	0.07	0.12	<0.01	0.32	remainder	—	0.07	0.09	0.07	0.19	
No. 62	Compar- ative Example	17.00	1.12	0.42	0.59	0.04	0.06	0.07	<0.01	0.28	remainder	14.75	0.63	1.50	0.56	0.13	
No. 63	Compar- ative Example	17.45	1.14	0.36	0.06	0.74	0.07	0.06	<0.01	0.35	remainder	0.08	0.80	2.22	0.70	0.13	
No. 64	Compar- ative Example	13.25	0.18	0.79	0.04	0.00	0.15	0.21	<0.01	0.25	remainder	—	0.04	0.05	0.22	0.36	
No. 65	Compar- ative Example	13.02	0.36	0.81	0.05	0.00	0.08	0.19	<0.01	0.19	remainder	—	0.05	0.06	0.14	0.27	
No. 66	Compar- ative Example	16.28	1.04	0.25	0.00	0.00	0.31	0.00	<0.01	0.42	remainder	—	0.00	0.00	0.00	0.31	
No. 67	Compar- ative Example	16.28	1.04	0.25	0.00	0.00	0.31	0.00	<0.01	0.42	remainder	—	0.00	0.00	0.00	0.31	HIP

[0294] In Tables 1 and 2, among the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0295] Each sintered body contained very small amounts of impurities, but the description thereof in Tables 1 and 2 is omitted.

Sample No. 68

[0296] (1) First, a metal powder having a composition shown in Table 3 was produced by a water atomization method in the same manner as in the case of sample No. 1.

[0297] (2) Subsequently, the metal powder was granulated by a spray drying method. The binder used at this time was polyvinyl alcohol, which was used in an amount of 1 part by mass with respect to 100 parts by mass of the metal powder. Further, a solvent (ion exchanged water) was used in an amount of 50 parts by mass with respect to 1 part by mass of polyvinyl alcohol. In this manner, a granulated powder having an average particle diameter of 50 μm was obtained.

[0298] (3) Subsequently, this granulated powder was subjected to powder compacting under the following molding conditions. In this molding, a press molding machine was used. The shape of the molded body to be produced was determined to be a cube with a side length of 20 mm.

[0299] Molding Conditions

[0300] Material temperature: 90° C.

[0301] Molding pressure: 600 MPa (6 t/cm^2)

[0302] (4) Subsequently, the obtained molded body was subjected to a heat treatment (degreasing treatment) under the following degreasing conditions, whereby a degreased body was obtained.

[0303] Degreasing Conditions

[0304] Degreasing temperature: 450° C.

[0305] Degreasing time: 2 hours (retention time at the degreasing temperature)

[0306] Degreasing atmosphere: nitrogen atmosphere

[0307] (5) Subsequently, the obtained degreased body was fired under the following firing conditions, whereby a sintered body was obtained.

[0308] Firing Conditions

[0309] Firing temperature: 1200° C.

[0310] Firing time: 3 hours (retention time at the firing temperature)

[0311] Firing atmosphere: argon atmosphere

[0312] (6) Subsequently, the obtained sintered body was subjected to a quenching treatment under the following conditions.

[0313] Quenching Treatment Conditions

[0314] Quenching temperature: 980° C.

[0315] Quenching time: 4 hours

[0316] Quenching atmosphere: argon atmosphere

[0317] Cooling method: water cooling

[0318] (7) Subsequently, the sintered body having undergone the quenching treatment was subjected to a sub-zero treatment under the following conditions.

[0319] Sub-Zero Treatment Conditions

[0320] Sub-zero treatment temperature: −196° C.

[0321] Sub-zero treatment time: 2 hours

[0322] (8) Subsequently, the sintered body having undergone the sub-zero treatment was subjected to a tempering treatment under the following conditions.

[0323] Tempering Treatment Conditions

[0324] Tempering treatment temperature: 210° C.

[0325] Tempering treatment time: 4 hours

Sample Nos. 69 to 84

[0326] Sintered bodies were obtained in the same manner as in the case of sample No. 68 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 3, respectively. The sintered body of sample No. 84 was obtained by performing an HIP treatment under the following conditions after firing.

[0327] HIP Treatment Conditions

[0328] Heating temperature: 1100° C.

[0329] Heating time: 2 hours

[0330] Applied pressure: 100 MPa

TABLE 3

		Metal powder for powder metallurgy																
		Alloy composition												(E1 + E2)/Si	(E1 + E2)/C		
Sample No.	—	Cr	C	Si	E1 (Zr)	E2 (Nb)	Mn	Ni	Cu	O	Fe	E1/E2	E1 + E2			Mn + Ni	Remarks
		mass %										—	mass %	—	—	mass %	—
No. 68	Example	12.88	0.90	0.73	0.07	0.07	0.10	0.07	<0.01	0.27	remainder	1.00	0.14	0.19	0.16	0.17	Powder compacting
No. 69	Example	14.24	0.28	0.58	0.09	0.05	0.12	0.05	<0.01	0.24	remainder	1.80	0.14	0.24	0.50	0.17	Powder compacting
No. 70	Example	11.63	1.13	0.78	0.05	0.06	0.07	0.05	<0.01	0.31	remainder	0.83	0.11	0.14	0.10	0.12	Powder compacting
No. 71	Example	13.37	0.85	0.64	0.10	0.05	0.08	0.10	<0.01	0.25	remainder	2.00	0.15	0.23	0.18	0.18	Powder compacting
No. 72	Example	12.54	0.98	0.75	0.05	0.10	0.11	0.06	<0.01	0.29	remainder	0.50	0.15	0.20	0.15	0.17	Powder compacting
No. 73	Example	11.23	0.47	0.52	0.12	0.04	0.12	0.12	<0.01	0.22	remainder	3.00	0.16	0.31	0.34	0.24	Powder compacting
No. 74	Example	14.87	0.98	0.69	0.04	0.12	0.09	0.05	<0.01	0.41	remainder	0.33	0.16	0.23	0.16	0.14	Powder compacting
No. 75	Example	12.64	0.74	0.77	0.11	0.09	0.08	0.08	<0.01	0.30	remainder	1.22	0.20	0.26	0.27	0.16	Powder compacting
No. 76	Example	13.89	0.65	0.51	0.05	0.05	0.11	0.05	<0.01	0.28	remainder	1.00	0.10	0.20	0.15	0.16	Powder compacting
No. 77	Example	10.56	0.78	0.32	0.08	0.09	0.18	0.15	<0.01	0.25	remainder	0.89	0.17	0.53	0.22	0.33	Powder compacting
No. 78	Example	16.26	1.05	0.62	0.08	0.06	0.05	0.07	<0.01	0.29	remainder	1.33	0.14	0.23	0.13	0.12	Powder compacting
No. 79	Comparative Example	12.54	0.95	0.82	0.00	0.05	0.12	0.08	<0.01	0.25	remainder	0.00	0.05	0.06	0.05	0.20	Powder compacting
No. 80	Comparative Example	12.95	0.76	0.78	0.04	0.00	0.08	0.10	<0.01	0.31	remainder	—	0.04	0.05	0.05	0.18	Powder compacting
No. 81	Comparative Example	13.25	0.45	0.42	0.68	0.05	0.08	0.06	<0.01	0.27	remainder	13.60	0.73	1.74	1.62	0.14	Powder compacting
No. 82	Comparative Example	13.58	0.58	0.36	0.03	0.62	0.07	0.05	<0.01	0.32	remainder	0.05	0.65	1.81	1.12	0.12	Powder compacting
No. 83	Comparative Example	13.50	1.00	0.75	0.00	0.00	0.12	0.11	<0.01	0.33	remainder	—	0.00	0.00	0.00	0.23	Powder compacting
No. 84	Comparative Example	13.50	1.00	0.75	0.00	0.00	0.12	0.11	<0.01	0.33	remainder	—	0.00	0.00	0.00	0.23	HIP

[0331] In Table 3, among the metal powders for powder metallurgy and the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0332] Each sintered body contained very small amounts of impurities, but the description thereof in Table 3 is omitted.

2. Evaluation of Metal Powder (Zr—Nb Based)

[0333] With respect to the cross sections of the particles of the metal powders for powder metallurgy of the respective sample Nos. shown in Tables 1 to 3, the crystal structure was evaluated by TEM.

[0334] As a result, in all the metal powders for powder metallurgy corresponding to Example, the average number of the Fe-based alloy crystals was 1 or more and 5 or less. Specifically, the lowest average number was 1.2 and the highest average number was 4.6.

[0335] Further, in all the metal powders for powder metallurgy corresponding to Example, the circle equivalent diameter of the Fe-based alloy crystal was 1% or more and 100% or less the circle equivalent diameter of the particle. Specifically, the lowest ratio of the circle equivalent diameter of the Fe-based alloy crystal to the circle equivalent diameter of the particle was 2%, and the highest ratio thereof was 84%.

[0336] On the other hand, in all the metal powders for powder metallurgy corresponding to Comparative Example, the average number of the Fe-based alloy crystals was 6 or more. Specifically, the lowest average number was 8.4 and the highest average number was 256.

[0337] Although not shown in the respective tables, when the same evaluation as described above was performed also with respect to metal powders having the same compositions shown in Tables 1 to 3 except that both Mn and Ni were not contained, the average number of the Fe-based alloy crystals contained in the particle of each of the metal powders for powder metallurgy corresponding to Example was 1 or more and 5 or less as having been expected.

3. Evaluation of Sintered Body (Zr—Nb Based)

3.1 Evaluation of Relative Density

[0338] With respect to the sintered bodies of the respective sample Nos. shown in Tables 1 to 3, the sintered density was measured in accordance with the method for measuring the density of sintered metal materials specified in JIS Z 2501 (2000), and also the relative density of each sintered body was calculated with reference to the true density of the metal powder for powder metallurgy used for producing each sintered body.

[0339] The calculation results are shown in Tables 4 to 6.

3.2 Evaluation of Hardness

[0340] With respect to the sintered bodies of the respective sample Nos. shown in Tables 1 to 3, the Vickers hardness was measured in accordance with the Vickers hardness test method specified in JIS Z 2244 (2009).

[0341] Then, the measured hardness was evaluated according to the following evaluation criteria.

Evaluation Criteria for Vickers Hardness

[0342] A: The Vickers hardness is 495 or more.

[0343] F. The Vickers hardness is less than 495.

[0344] The evaluation results are shown in Tables 4 to 6.

3.3 Evaluation of Tensile Strength, 0.2% Proof Stress, and Elongation

[0345] With respect to the sintered bodies of the respective sample Nos. shown in Tables 1 to 3, the tensile strength, 0.2% proof stress, and elongation were measured in accordance with the metal material tensile test method specified in JIS Z 2241 (2011).

[0346] Then, the measured values of these physical properties were evaluated according to the following evaluation criteria.

Evaluation Criteria for Tensile Strength

[0347] A: The tensile strength of the sintered body is very high (1800 MPa or more).

[0348] B: The tensile strength of the sintered body is high (1600 MPa or more and less than 1800 MPa).

[0349] C: The tensile strength of the sintered body is slightly high (1400 MPa or more and less than 1600 MPa).

[0350] D: The tensile strength of the sintered body is slightly low (1200 MPa or more and less than 1400 MPa).

[0351] E: The tensile strength of the sintered body is low (1000 MPa or more and less than 1200 MPa).

[0352] F: The tensile strength of the sintered body is very low (800 MPa or more and less than 1000 MPa).

[0353] G: The tensile strength of the sintered body is particularly low (less than 800 MPa).

Evaluation Criteria for 0.2% Proof Stress

[0354] A: The 0.2% proof stress of the sintered body is very high (1200 MPa or more).

[0355] B: The 0.2% proof stress of the sintered body is high (1100 MPa or more and less than 1200 MPa).

[0356] C: The 0.2% proof stress of the sintered body is slightly high (1000 MPa or more and less than 1100 MPa).

[0357] D: The 0.2% proof stress of the sintered body is slightly low (900 MPa or more and less than 1000 MPa).

[0358] E: The 0.2% proof stress of the sintered body is low (800 MPa or more and less than 900 MPa).

[0359] F: The 0.2% proof stress of the sintered body is very low (700 MPa or more and less than 800 MPa).

[0360] G: The 0.2% proof stress of the sintered body is particularly low (less than 700 MPa).

Evaluation Criteria for Elongation

[0361] A: The elongation of the sintered body is very large (7% or more).

[0362] B: The elongation of the sintered body is large (6% or more and less than 7%).

[0363] C: The elongation of the sintered body is slightly large (5% or more and less than 6%).

[0364] D: The elongation of the sintered body is slightly small (4% or more and less than 5%).

[0365] E: The elongation of the sintered body is small (3% or more and less than 4%).

[0366] F: The elongation of the sintered body is very small (2% or more and less than 3%).

[0367] G: The elongation of the sintered body is particularly small (less than 2%).

[0368] The above evaluation results are shown in Tables 4 to 6.

3.4 Evaluation of Fatigue Strength

[0369] With respect to the sintered bodies of the respective sample Nos. shown in Tables 1 to 3, the fatigue strength was measured.

[0370] The fatigue strength was measured in accordance with the test method specified in JIS Z 2273 (1978). The waveform of an applied load corresponding to a repeated stress was set to an alternating sine wave, and the minimum/maximum stress ratio (minimum stress/maximum stress) was set to 0.1. Further, the repeated frequency was set to 30 Hz, and the repeat count was set to 1×10^7.

[0371] Then, the measured fatigue strength was evaluated according to the following evaluation criteria.

Evaluation Criteria for Fatigue Strength

[0372] A: The fatigue strength of the sintered body is 575 MPa or more.

[0373] B: The fatigue strength of the sintered body is 555 MPa or more and less than 575 MPa.

[0374] C: The fatigue strength of the sintered body is 535 MPa or more and less than 555 MPa.

[0375] D: The fatigue strength of the sintered body is 515 MPa or more and less than 535 MPa.

[0376] E: The fatigue strength of the sintered body is 495 MPa or more and less than 515 MPa.

[0377] F: The fatigue strength of the sintered body is less than 495 MPa.

[0378] The above evaluation results are shown in Tables 4 to 6.

TABLE 4

		Metal powder	Evaluation results of sintered body					
Sample No.	—	Average particle diameter μm	Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 1	Example	3.86	99.5	A	A	A	A	A
No. 2	Example	3.79	98.2	A	B	B	B	B
No. 3	Example	3.84	98.4	A	B	B	B	B
No. 4	Example	3.92	99.3	A	A	A	A	A
No. 5	Example	4.02	99.4	A	A	A	A	A
No. 6	Example	3.68	97.8	A	B	B	B	B
No. 7	Example	3.77	98.2	A	B	B	B	B
No. 8	Example	3.81	98.8	A	A	A	B	B
No. 9	Example	3.85	98.9	A	A	A	B	B
No. 10	Example	4.05	98.5	A	B	B	B	B
No. 11	Example	3.97	98.9	A	A	A	B	B
No. 12	Example	3.92	98.6	A	B	B	B	B
No. 13	Example	3.74	97.5	A	B	B	C	C
No. 14	Example	3.81	97.2	A	B	B	B	B
No. 15	Example	3.86	97.4	A	B	B	B	B
No. 16	Example	3.88	97.1	A	B	B	B	B
No. 17	Example	3.76	97.2	A	B	B	B	B
No. 18	Example	3.84	97.0	A	C	C	B	B
No. 19	Example	3.84	97.2	A	B	B	C	C
No. 20	Example	3.86	96.8	A	C	C	C	C
No. 21	Example	3.76	97.3	A	B	B	B	B
No. 22	Example	3.77	95.8	A	D	D	B	B
No. 23	Example	3.94	96.2	A	D	C	B	B
No. 24	Example	3.05	95.7	A	D	D	D	D
No. 25	Example	3.12	95.6	A	D	D	D	D
No. 26	Example	3.09	95.5	A	D	D	D	D
No. 27	Example	2.85	95.1	A	D	D	D	D
No. 28	Example	7.84	99.1	A	A	A	A	A
No. 29	Example	8.04	99.2	A	A	A	A	A
No. 30	Example	7.23	98.3	A	B	B	B	B
No. 31	Comparative Example	3.67	93.8	F	F	F	C	C
No. 32	Comparative Example	3.48	94.5	F	E	C	C	C
No. 33	Comparative Example	2.97	94.8	F	E	E	D	D
No. 34	Comparative Example	3.05	93.2	F	F	F	D	D
No. 35	Comparative Example	2.16	93.1	F	F	F	F	F

TABLE 4-continued

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 36	Comparative Example	3.04	99.2	A	A	A	B	B

TABLE 5

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 37	Example	4.15	99.5	A	A	A	A	A
No. 38	Example	4.03	99.6	A	A	A	A	A
No. 39	Example	4.25	98.3	A	B	B	B	B
No. 40	Example	4.05	97.6	A	B	B	B	B
No. 41	Example	3.98	97.5	A	B	B	B	B
No. 42	Example	4.23	99.1	A	B	B	B	B
No. 43	Example	5.36	99.2	A	B	B	B	B
No. 44	Example	4.05	97.6	A	B	B	B	B
No. 45	Example	4.14	99.3	A	A	A	B	B
No. 46	Example	4.58	98.4	A	B	B	B	B
No. 47	Example	6.35	98.9	A	B	B	C	C
No. 48	Example	4.45	99.1	A	C	C	B	B
No. 49	Example	10.8	98.9	A	C	C	C	C
No. 50	Example	4.78	95.9	A	D	D	B	B
No. 51	Example	4.69	96.4	A	D	C	B	B
No. 52	Example	4.36	95.7	A	D	D	D	D
No. 53	Example	4.12	95.6	A	D	D	D	D
No. 54	Example	15.4	95.4	A	D	D	D	D
No. 55	Example	4.23	99.1	A	B	B	B	B
No. 56	Example	3.87	99.3	A	A	A	A	A
No. 57	Example	8.31	99.3	A	A	A	A	A
No. 58	Example	8.06	99.4	A	A	A	A	A
No. 59	Example	8.52	98.1	A	B	B	B	B
No. 60	Comparative Example	4.58	93.7	A	F	F	C	C
No. 61	Comparative Example	4.49	94.4	A	E	C	C	C
No. 62	Comparative Example	4.79	94.7	A	E	E	D	D
No. 63	Comparative Example	4.56	93.6	A	F	F	D	D
No. 64	Comparative Example	4.35	94.9	A	F	F	F	F
No. 65	Comparative Example	3.78	94.6	A	E	E	E	E
No. 66	Comparative Example	2.28	93.3	F	B	B	F	F
No. 67	Comparative Example	2.28	98.8	A	A	A	B	B

TABLE 6

Sample No.	—	Metal powder Average particle diameter μm	Evaluation results of sintered body Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 68	Example	3.86	99.6	A	A	A	A	A
No. 69	Example	3.79	98.5	A	B	B	B	B
No. 70	Example	3.84	98.6	A	B	B	B	B
No. 71	Example	3.92	99.5	A	A	A	A	A
No. 72	Example	4.02	99.6	A	A	A	A	A
No. 73	Example	3.68	98.1	A	B	B	B	B
No. 74	Example	3.77	98.4	A	B	B	B	B
No. 75	Example	3.81	98.9	A	A	A	B	B
No. 76	Example	3.85	99.1	A	A	A	B	B
No. 77	Example	4.05	98.7	A	B	B	B	B
No. 78	Example	3.97	99.1	A	A	A	B	B
No. 79	Comparative Example	3.67	94.0	F	E	D	C	C
No. 80	Comparative Example	3.48	94.6	F	E	C	C	C
No. 81	Comparative Example	2.97	94.9	A	E	D	D	D
No. 82	Comparative Example	3.05	93.5	F	F	E	D	D
No. 83	Comparative Example	2.16	93.3	F	F	F	F	F
No. 84	Comparative Example	3.04	99.3	A	A	A	B	B

[0379] As apparent from Tables 4 to 6, it was confirmed that the sintered bodies corresponding to Example each have a higher relative density than the sintered bodies corresponding to Comparative Example (excluding the sintered bodies having undergone the HIP treatment). Further, it was also confirmed that there is a significant difference in properties such as tensile strength, 0.2% proof stress, elongation, and fatigue strength between the sintered bodies corresponding to Example and the sintered bodies corresponding to Comparative Example (excluding the sintered bodies having undergone the HIP treatment).

[0380] On the other hand, by comparison of the values of the respective physical properties between the sintered bodies corresponding to Example and the sintered bodies having undergone the HIP treatment, it was confirmed that the values of the physical properties are all comparable to each other.

[0381] Although not shown in the respective tables, when the same evaluation as described above was performed also with respect to sintered bodies produced by using the metal powders having the same compositions shown in Tables 1 to 3 except that both Mn and Ni were not contained, the relative density and the mechanical properties of the sintered bodies produced by using the metal powders for powder metallurgy corresponding to Example were all favorable as having been expected.

4. Production of Sintered Body (Hf—Nb Based)

Sample Nos. 85 to 105

[0382] Sintered bodies were obtained in the same manner as the method for producing the sintered body of sample No. 1 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 7, respectively. The sintered body of sample No. 105 was obtained by performing an HIP treatment under the following conditions after firing.

[0383] HIP Treatment Conditions

[0384] Heating temperature: 1100° C.

[0385] Heating time: 2 hours

[0386] Applied pressure: 100 MPa

TABLE 7

Sample No.	—	Metal powder for powder metallurgy: Alloy composition: Cr mass %	C mass %	Si mass %	E1 (Zr) mass %	E2 (Nb) mass %	Mn mass %	Ni mass %	Cu mass %	O mass %	Fe	E1/E2 —	E1 + E2 mass %	(E1 + E2)/Si —	(E1 + E2)/C —	Mn + Ni mass %	Remarks —
No. 85	Example	12.85	0.91	0.72	0.09	0.05	0.11	0.08	<0.01	0.29	remainder	1.80	0.14	0.19	0.15	0.19	
No. 86	Example	14.22	0.29	0.59	0.07	0.07	0.13	0.06	<0.01	0.25	remainder	1.00	0.14	0.24	0.48	0.19	
No. 87	Example	11.58	1.12	0.79	0.15	0.05	0.07	0.12	<0.01	0.32	remainder	3.00	0.20	0.25	0.18	0.19	
No. 88	Example	13.42	0.84	0.65	0.11	0.06	0.08	0.11	<0.01	0.24	remainder	1.83	0.17	0.26	0.20	0.19	
No. 89	Example	12.55	0.96	0.75	0.06	0.08	0.11	0.07	<0.01	0.31	remainder	0.75	0.14	0.19	0.15	0.18	
No. 90	Example	10.53	0.77	0.34	0.13	0.07	0.18	0.15	<0.01	0.25	remainder	1.86	0.20	0.59	0.26	0.33	
No. 91	Example	16.28	1.04	0.63	0.08	0.06	0.07	0.08	<0.01	0.28	remainder	1.33	0.14	0.22	0.13	0.15	
No. 92	Example	19.76	0.92	0.86	0.12	0.08	0.04	0.08	<0.01	0.45	remainder	1.50	0.20	0.23	0.22	0.12	
No. 93	Example	23.51	0.43	0.46	0.08	0.04	0.07	0.06	<0.01	0.65	remainder	2.00	0.12	0.26	0.28	0.13	
No. 94	Example	12.75	0.86	0.76	0.11	0.05	0.01	0.06	<0.01	0.25	remainder	2.20	0.16	0.21	0.19	0.07	
No. 95	Example	12.82	0.88	0.74	0.09	0.03	0.99	0.58	<0.01	0.23	remainder	3.00	0.12	0.16	0.14	1.57	
No. 96	Example	12.73	0.92	0.71	0.03	0.07	0.10	0.08	<0.01	0.29	remainder	0.43	0.10	0.14	0.11	0.18	
No. 97	Example	13.01	1.01	0.80	0.05	0.03	0.08	0.07	<0.01	0.31	remainder	1.67	0.08	0.10	0.08	0.15	
No. 98	Example	14.38	0.45	0.76	0.08	0.11	0.05	0.04	<0.01	0.41	remainder	0.73	0.19	0.25	0.42	0.09	
No. 99	Example	12.78	0.78	0.72	0.39	0.28	0.11	0.07	<0.01	0.29	remainder	1.39	0.67	0.93	0.86	0.18	
No. 100	Comparative Example	12.56	093	0.81	0.00	0.06	0.12	0.07	<0.01	0.26	remainder	0.00	0.06	0.07	0.06	0.19	
No. 101	Comparative Example	12.97	0.75	0.76	0.06	0.00	0.09	0.11	<0.01	0.32	remainder	—	0.06	0.08	0.08	0.20	
No. 102	Comparative Example	13.27	0.46	0.43	0.71	0.07	0.09	0.05	<0.01	0.28	remainder	10.14	0.78	1.81	1.70	0.14	
No. 103	Comparative Example	13.55	0.59	0.35	0.03	0.68	0.07	0.06	<0.01	0.33	remainder	0.04	0.71	2.03	1.20	0.13	
No. 104	Comparative Example	13.52	0.98	0.74	0.00	0.00	0.11	0.08	<0.01	0.32	remainder	—	0.00	0.00	0.00	0.19	
No. 105	Comparative Example	13.52	0.98	0.74	0.00	0.00	0.11	0.08	<0.01	0.32	remainder	—	0.00	0.00	0.00	0.19	HIP

[0387] In Table 7, among the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0388] Each sintered body contained very small amounts of impurities, but the description thereof in Table 7 is omitted.

5. Evaluation of Metal Powder (Hf—Nb Based)

[0389] With respect to the cross sections of the particles of the metal powders for powder metallurgy of the respective sample Nos. shown in Table 7, the crystal structure was evaluated by TEM.

[0390] As a result, in all the metal powders for powder metallurgy corresponding to Example, the average number of the Fe-based alloy crystals was 1 or more and 5 or less. Further, in all the metal powders for powder metallurgy corresponding to Example, the circle equivalent diameter of the Fe-based alloy crystal was 1% or more and 100% or less the circle equivalent diameter of the particle.

[0391] On the other hand, in all the metal powders for powder metallurgy corresponding to Comparative Example, the average number of the Fe-based alloy crystals was 6 or more.

6. Evaluation of Sintered Body (Hf—Nb Based)

6.1 Evaluation of Relative Density

[0392] With respect to the sintered bodies of the respective sample Nos. shown in Table 7, the sintered density was measured in accordance with the method for measuring the density of sintered metal materials specified in JIS Z 2501 (2000), and also the relative density of each sintered body was calculated with reference to the true density of the metal powder for powder metallurgy used for producing each sintered body.

[0393] The calculation results are shown in Table 8.

6.2 Evaluation of Hardness

[0394] With respect to the sintered bodies of the respective sample Nos. shown in Table 7, the Vickers hardness was measured in accordance with the Vickers hardness test method specified in JIS Z 2244 (2009).

[0395] Then, the measured hardness was evaluated according to the evaluation criteria described in 3.2.

[0396] The evaluation results are shown in Table 8.

6.3 Evaluation of Tensile Strength, 0.2% Proof Stress, and Elongation

[0397] With respect to the sintered bodies of the respective sample Nos. shown in Table 7, the tensile strength, 0.2% proof stress, and elongation were measured in accordance with the metal material tensile test method specified in JIS Z 2241 (2011).

[0398] Then, the measured values of the physical properties were evaluated according to the evaluation criteria described in 3.3.

[0399] The evaluation results are shown in Table 8.

6.4 Evaluation of Fatigue Strength

[0400] With respect to the sintered bodies of the respective sample Nos. shown in Table 7, the fatigue strength was measured in the same manner as in 3.4.

[0401] Then, the measured fatigue strength was evaluated according to the evaluation criteria described in 3.4.

[0402] The evaluation results are shown in Table 8.

TABLE 8

		Metal powder	Evaluation results of sintered body					
Sample No.	—	Average particle diameter μm	Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 85	Example	4.12	99.4	A	A	A	A	A
No. 86	Example	4.79	98.3	A	B	B	B	B
No. 87	Example	3.84	98.7	A	A	A	B	B
No. 88	Example	5.92	99.4	A	A	A	A	A
No. 89	Example	7.02	99.2	A	A	A	A	A
No. 90	Example	2.08	98.6	A	B	B	B	B
No. 91	Example	2.89	99.0	A	A	A	A	B
No. 92	Example	3.92	98.7	A	B	B	B	B
No. 93	Example	3.74	98.2	A	B	B	B	B
No. 94	Example	9.87	98.9	A	A	A	B	C
No. 95	Example	15.46	98.6	A	A	A	B	C
No. 96	Example	23.48	98.8	A	A	A	B	C
No. 97	Example	11.59	98.5	A	B	B	B	B
No. 98	Example	4.25	98.8	A	B	B	B	B
No. 99	Example	2.51	98.1	A	B	B	B	C
No. 100	Comparative Example	4.23	94.6	F	E	E	C	C
No. 101	Comparative Example	4.56	94.8	F	E	E	D	D
No. 102	Comparative Example	4.79	95.1	F	E	E	D	D
No. 103	Comparative Example	4.69	94.1	F	F	F	D	D
No. 104	Comparative Example	6.21	93.4	F	F	F	F	F
No. 105	Comparative Example	6.21	99.0	A	A	A	B	B

[0403] As apparent from Table 8, it was confirmed that the sintered bodies corresponding to Example each have a higher relative density than the sintered bodies corresponding to Comparative Example (excluding the sintered body having undergone the HIP treatment). Further, it was also confirmed that there is a significant difference in properties such as tensile strength, 0.2% proof stress, elongation, and fatigue strength between the sintered bodies corresponding to Example and the sintered bodies corresponding to Comparative Example (excluding the sintered body having undergone the HIP treatment).

[0404] On the other hand, by comparison of the values of the respective physical properties between the sintered bodies corresponding to Example and the sintered body having undergone the HIP treatment, it was confirmed that the values of the physical properties are all comparable to each other.

7. Production of Sintered Body (Ti—Nb Based)

Sample Nos. 106 to 118

[0405] Sintered bodies were obtained in the same manner as the method for producing the sintered body of sample No. 1 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 9, respectively.

Sample No. 119

[0406] A metal powder, a Ti powder having an average particle diameter of 40 μm, and a Nb powder having an average particle diameter of 25 μm were mixed, whereby a mixed powder was prepared. In the preparation of the mixed powder, each of the mixing amounts of the metal powder, the Ti powder, and the Nb powder was adjusted so that the composition of the mixed powder was as shown in Table 9.

[0407] Then, a sintered body was obtained in the same manner as the method for producing the sintered body of sample No. 1 using this mixed powder.

sured in accordance with the method for measuring the density of sintered metal materials specified in JIS Z 2501 (2000), and also the relative density of each sintered body was calcu-

TABLE 9

		Metal powder for powder metallurgy																
		Alloy composition												(E1 +	(E1 +			
Sample No.	—	Cr	C	Si	E1 (Ti)	E2 (Nb)	Mn	Ni	Cu	O	Fe	E1/ E2	E1 + E2	E2)/ Si	E2)/ C	Mn + Ni	Re- marks	
		mass %										—	mass %	—	—	mass %	—	
No. 106	Example	12.91	0.87	0.74	0.05	0.09	0.10	0.09	<0.01	0.28	remainder	0.56	0.14	0.19	0.16	0.19		
No. 107	Example	14.25	0.31	0.55	0.07	0.07	0.16	0.06	<0.01	0.24	remainder	1.00	0.14	0.25	0.45	0.22		
No. 108	Example	11.43	1.20	0.83	0.06	0.15	0.07	0.13	<0.01	0.29	remainder	0.40	0.21	0.25	0.18	0.20		
No. 109	Example	12.84	0.86	0.75	0.06	0.05	1.05	0.51	<0.01	0.25	remainder	1.20	0.11	0.15	0.13	1.56		
No. 110	Example	12.71	0.94	0.45	0.02	0.06	0.28	0.22	<0.01	0.29	remainder	0.33	0.08	0.18	0.09	0.50		
No. 111	Example	13.11	1.02	0.81	0.04	0.03	0.54	0.15	<0.01	0.31	remainder	1.33	0.07	0.09	0.07	0.69		
No. 112	Example	14.42	0.43	0.78	0.08	0.11	0.15	0.06	<0.01	0.38	remainder	0.73	0.19	0.24	0.44	0.21		
No. 113	Example	12.77	0.76	0.71	0.41	0.32	0.09	0.08	<0.01	0.29	remainder	1.28	0.73	1.03	0.96	0.17		
No. 114	Comparative Example	12.56	0.92	0.83	0.00	0.07	0.14	0.08	<0.01	0.25	remainder	0.00	0.07	0.08	0.08	0.22		
No. 115	Comparative Example	12.95	0.74	0.78	0.07	0.00	0.11	0.15	<0.01	0.34	remainder	—	0.07	0.09	0.09	0.26		
No. 116	Comparative Example	13.26	0.45	0.42	0.73	0.07	0.12	0.06	<0.01	0.28	remainder	10.43	0.80	1.90	1.78	0.18		
No. 117	Comparative Example	13.53	0.57	0.36	0.04	0.69	0.08	0.14	<0.01	0.34	remainder	0.06	0.73	2.03	1.28	0.22		
No. 118	Comparative Example	13.58	0.96	0.75	0.00	0.00	0.13	0.06	<0.01	0.35	remainder	—	0.00	0.00	0.00	0.19		
No. 119	Comparative Example	13.50	0.89	0.71	0.25	0.42	0.11	0.08	<0.01	0.48	remainder	0.60	0.67	0.94	0.75	0.19	Mixed powder	

[0408] In Table 9, among the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0409] Each sintered body contained very small amounts of impurities, but the description thereof in Table 9 is omitted.

8. Evaluation of Metal Powder (Ti—Nb Based)

[0410] With respect to the cross sections of the particles of the metal powders for powder metallurgy of the respective sample Nos. shown in Table 9, the crystal structure was evaluated by TEM.

[0411] As a result, in all the metal powders for powder metallurgy corresponding to Example, the average number of the Fe-based alloy crystals was 1 or more and 5 or less. Further, in all the metal powders for powder metallurgy corresponding to Example, the circle equivalent diameter of the Fe-based alloy crystal was 1% or more and 100% or less the circle equivalent diameter of the particle.

[0412] On the other hand, in all the metal powders for powder metallurgy corresponding to Comparative Example, the average number of the Fe-based alloy crystals was 6 or more.

9. Evaluation of Sintered Body (Ti—Nb Based)

9.1 Evaluation of Relative Density

[0413] With respect to the sintered bodies of the respective sample Nos. shown in Table 9, the sintered density was measured with reference to the true density of the metal powder for powder metallurgy used for producing each sintered body.

[0414] The calculation results are shown in Table 10.

9.2 Evaluation of Hardness

[0415] With respect to the sintered bodies of the respective sample Nos. shown in Table 9, the Vickers hardness was measured in accordance with the Vickers hardness test method specified in JIS Z 2244 (2009).

[0416] Then, the measured hardness was evaluated according to the evaluation criteria described in 3.2.

[0417] The evaluation results are shown in Table 10.

9.3 Evaluation of Tensile Strength, 0.2% Proof Stress, and Elongation

[0418] With respect to the sintered bodies of the respective sample Nos. shown in Table 9, the tensile strength, 0.2% proof stress, and elongation were measured in accordance with the metal material tensile test method specified in JIS Z 2241 (2011).

[0419] Then, the measured values of the physical properties were evaluated according to the above-mentioned evaluation criteria described in 3.3.

[0420] The evaluation results are shown in Table 10.

9.4 Evaluation of Fatigue Strength

[0421] With respect to the sintered bodies of the respective sample Nos. shown in Table 9, the fatigue strength was measured in the same manner as in 3.4.

[0422] Then, the measured fatigue strength was evaluated according to the evaluation criteria described in 3.4.

[0423] The evaluation results are shown in Table 10.

TABLE 10

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 106	Example	4.15	99.2	A	A	A	A	A
No. 107	Example	5.74	98.5	A	B	B	B	B
No. 108	Example	3.46	98.6	A	B	B	B	B
No. 109	Example	9.57	98.3	A	B	B	B	C
No. 110	Example	4.75	98.8	A	A	A	B	B
No. 111	Example	14.68	98.2	A	B	B	B	C
No. 112	Example	3.78	99.0	A	A	A	A	B
No. 113	Example	2.08	98.0	A	B	B	C	C
No. 114	Comparative Example	4.55	94.5	F	E	E	D	D
No. 115	Comparative Example	3.97	95.1	F	E	E	D	D
No. 116	Comparative Example	2.78	95.3	F	E	E	D	D
No. 117	Comparative Example	3.08	93.8	F	F	F	D	D
No. 118	Comparative Example	2.04	93.4	F	F	F	F	F
No. 119	Comparative Example	4.29	95.6	A	C	C	D	D

[0424] As apparent from Table 10, it was confirmed that the sintered bodies corresponding to Example each have a higher relative density than the sintered bodies corresponding to Comparative Example. It was also confirmed that there is a significant difference in properties such as tensile strength, 0.2% proof stress, elongation, and fatigue strength between the sintered bodies corresponding to Example and the sintered bodies corresponding to Comparative Example.

10. Production of Sintered Body (Nb—Ta Based)

Sample Nos. 120 to 132

[0425] Sintered bodies were obtained in the same manner as the method for producing the sintered body of sample No. 1 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 11, respectively.

TABLE 11

Sample No.	—	Metal powder for powder metallurgy: Alloy composition: Cr mass %	C mass %	Si mass %	E1 (Nb) mass %	E2 (Ta) mass %	Mn mass %	Ni mass %	Cu mass %	O mass %	Fe mass %	E1/E2 —	E1 + E2 mass %	(E1 + E2)/Si —	(E1 + E2)/C —	Mn + Ni mass %	Remarks —
No. 120	Example	12.88	0.86	0.72	0.05	0.09	0.10	0.12	<0.01	0.26	remainder	0.56	0.14	0.19	0.16	0.22	
No. 121	Example	14.36	0.24	0.54	0.06	0.06	0.18	0.08	<0.01	0.24	remainder	1.00	0.12	0.22	0.50	0.26	
No. 122	Example	11.39	1.18	0.86	0.05	0.15	0.08	0.13	<0.01	0.31	remainder	0.33	0.20	0.23	0.17	0.21	
No. 123	Example	12.82	0.77	0.78	0.06	0.04	1.12	0.53	<0.01	0.45	remainder	1.50	0.10	0.13	0.13	1.65	
No. 124	Example	12.68	0.82	0.46	0.02	0.07	0.32	0.31	<0.01	0.39	remainder	0.29	0.09	0.20	0.11	0.63	
No. 125	Example	13.08	1.05	0.83	0.03	0.04	0.61	0.16	<0.01	0.32	remainder	0.75	0.07	0.08	0.07	0.77	
No. 126	Example	14.45	0.44	0.79	0.09	0.11	0.16	0.07	<0.01	0.39	remainder	0.82	0.20	0.25	0.45	0.23	
No. 127	Example	12.75	0.74	0.72	0.43	0.28	0.10	0.05	<0.01	0.25	remainder	1.54	0.71	0.99	0.96	0.15	
No. 128	Comparative Example	12.64	0.93	0.87	0.00	0.09	0.16	0.12	<0.01	0.36	remainder	0.00	0.09	0.10	0.10	0.28	
No. 129	Comparative Example	12.97	0.72	0.76	0.11	0.00	0.15	0.09	<0.01	0.36	remainder	—	0.11	0.14	0.15	0.24	

TABLE 11-continued

Sample No.	—	Metal powder for powder metallurgy: Alloy composition: Cr	C	Si	E1 (Nb)	E2 (Ta)	Mn	Ni	Cu	O	Fe	E1/E2	E1 + E2	(E1 + E2)/Si	(E1 + E2)/C	Mn + Ni	Remarks
		mass %										—	mass %	—	—	mass %	—
No. 130	Comparative Example	13.31	0.42	0.41	0.78	0.07	0.15	0.05	<0.01	0.19	remainder	11.14	0.85	2.07	2.02	0.20	
No. 131	Comparative Example	13.56	0.59	0.35	0.05	0.75	0.06	0.15	<0.01	0.34	remainder	0.07	0.80	2.29	1.36	0.21	
No. 132	Comparative Example	13.54	0.97	0.73	0.00	0.00	0.12	0.08	<0.01	0.35	remainder	—	0.00	0.00	0.00	0.20	

[0426] In Table 11, among the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0427] Each sintered body contained very small amounts of impurities, but the description thereof in Table 11 is omitted.

11. Evaluation of Metal Powder (Nb—Ta Based)

[0428] With respect to the cross sections of the particles of the metal powders for powder metallurgy of the respective sample Nos. shown in Table 11, the crystal structure was evaluated by TEM.

[0429] As a result, in all the metal powders for powder metallurgy corresponding to Example, the average number of the Fe-based alloy crystals was 1 or more and 5 or less. Further, in all the metal powders for powder metallurgy corresponding to Example, the circle equivalent diameter of the Fe-based alloy crystal was 1% or more and 100% or less the circle equivalent diameter of the particle.

[0430] On the other hand, in all the metal powders for powder metallurgy corresponding to Comparative Example, the average number of the Fe-based alloy crystals was 6 or more.

12. Evaluation of Sintered Body (Nb—Ta Based)

12.1 Evaluation of Relative Density

[0431] With respect to the sintered bodies of the respective sample Nos. shown in Table 11, the sintered density was measured in accordance with the method for measuring the density of sintered metal materials specified in JIS Z 2501 (2000), and also the relative density of each sintered body was calculated with reference to the true density of the metal powder for powder metallurgy used for producing each sintered body.

[0432] The calculation results are shown in Table 12.

12.2 Evaluation of Hardness

[0433] With respect to the sintered bodies of the respective sample Nos. shown in Table 11, the Vickers hardness was measured in accordance with the Vickers hardness test method specified in JIS Z 2244 (2009).

[0434] Then, the measured hardness was evaluated according to the evaluation criteria described in 3.2.

[0435] The evaluation results are shown in Table 12.

12.3 Evaluation of Tensile Strength, 0.2% Proof Stress, and Elongation

[0436] With respect to the sintered bodies of the respective sample Nos. shown in Table 11, the tensile strength, 0.2% proof stress, and elongation were measured in accordance with the metal material tensile test method specified in JIS Z 2241 (2011).

[0437] Then, the measured values of the physical properties were evaluated according to the above-mentioned evaluation criteria described in 3.3.

[0438] The evaluation results are shown in Table 12.

12.4 Evaluation of Fatigue Strength

[0439] With respect to the sintered bodies of the respective sample Nos. shown in Table 11, the fatigue strength was measured in the same manner as in 3.4.

[0440] Then, the measured fatigue strength was evaluated according to the evaluation criteria described in 3.4.

[0441] The evaluation results are shown in Table 12.

TABLE 12

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 120	Example	4.22	98.9	A	A	A	A	A
No. 121	Example	5.78	98.2	A	B	B	B	B
No. 122	Example	3.35	98.1	A	B	B	B	B
No. 123	Example	9.05	97.8	A	B	B	B	C
No. 124	Example	4.89	98.5	A	B	B	B	B

TABLE 12-continued

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 125	Example	13.26	98.0	A	B	B	B	C
No. 126	Example	3.97	98.8	A	A	A	A	B
No. 127	Example	2.12	97.8	A	B	B	C	C
No. 128	Comparative Example	4.63	94.8	F	F	F	D	D
No. 129	Comparative Example	3.87	95.3	F	E	E	D	D
No. 130	Comparative Example	2.54	95.5	F	E	E	D	D
No. 131	Comparative Example	3.15	94.2	F	F	F	D	D
No. 132	Comparative Example	2.13	94.1	F	F	F	F	F

[0442] As apparent from Table 12, it was confirmed that the sintered bodies corresponding to Example each have a higher relative density than the sintered bodies corresponding to Comparative Example. It was also confirmed that there is a significant difference in properties such as tensile strength, 0.2% proof stress, elongation, and fatigue strength between the sintered bodies corresponding to Example and the sintered bodies corresponding to Comparative Example.

13. Production of Sintered Body (Y—Nb Based)

Sample Nos. 133 to 145

[0443] Sintered bodies were obtained in the same manner as the method for producing the sintered body of sample No. 1 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 13, respectively.

TABLE 13

Sample No.	—	Metal powder for powder metallurgy: Alloy composition: Cr mass %	C mass %	Si mass %	E1 (Y) mass %	E2 (Nb) mass %	Mn mass %	Ni mass %	Cu mass %	O mass %	Fe	E1/E2 —	E1 + E2 mass %	(E1 + E2)/Si —	(E1 + E2)/C —	Mn + Ni mass %	Remarks —
No. 133	Example	12.84	0.84	0.73	0.08	0.09	0.09	0.16	<0.01	0.25	remainder	0.89	0.17	0.23	0.20	0.25	
No. 134	Example	14.33	0.33	0.55	0.12	0.06	0.18	0.12	<0.01	0.24	remainder	2.00	0.18	0.33	0.55	0.30	
No. 135	Example	11.36	1.15	0.87	0.07	0.15	0.09	0.12	<0.01	0.31	remainder	0.47	0.22	0.25	0.19	0.21	
No. 136	Example	12.84	0.76	0.79	0.07	0.04	1.14	0.52	<0.01	0.46	remainder	1.75	0.11	0.14	0.14	1.66	
No. 137	Example	12.65	0.80	0.45	0.02	0.06	0.33	0.32	<0.01	0.40	remainder	0.33	0.08	0.18	0.10	0.65	
No. 138	Example	13.11	1.04	0.82	0.03	0.04	0.62	0.18	<0.01	0.29	remainder	0.75	0.07	0.09	0.07	0.80	
No. 139	Example	14.48	0.45	0.78	0.12	0.11	0.16	0.08	<0.01	0.41	remainder	1.09	0.23	0.29	0.51	0.24	
No. 140	Example	12.76	0.75	0.73	0.41	0.31	0.11	0.06	<0.01	0.28	remainder	1.32	0.72	0.99	0.96	0.17	
No. 141	Comparative Example	12.66	0.94	0.88	0.00	0.10	0.17	0.13	<0.01	0.37	remainder	0.00	0.10	0.11	0.11	0.30	
No. 142	Comparative Example	13.01	0.74	0.78	0.09	0.00	0.16	0.10	<0.01	0.35	remainder	—	0.09	0.12	0.12	0.26	
No. 143	Comparative Example	13.33	0.41	0.45	0.79	0.08	0.14	0.06	<0.01	0.22	remainder	9.88	0.87	1.93	2.12	0.20	
No. 144	Comparative Example	13.58	0.61	0.36	0.06	0.77	0.07	0.17	<0.01	0.36	remainder	0.08	0.83	2.31	1.36	0.24	

TABLE 13-continued

Sample No.	—	Metal powder for powder metallurgy: Alloy composition: Cr	C	Si	E1 (Y)	E2 (Nb)	Mn	Ni	Cu	O	Fe	E1/E2 —	E1 + E2 mass %	(E1 + E2)/Si —	(E1 + E2)/C —	Mn + Ni mass %	Remarks —
		mass %															
No. 145	Comparative Example	13.53	0.95	0.75	0.00	0.00	0.13	0.07	<0.01	0.34	remainder	—	0.00	0.00	0.00	0.20	

[0444] In Table 13, among the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0445] Each sintered body contained very small amounts of impurities, but the description thereof in Table 13 is omitted.

14. Evaluation of Metal Powder (Y—Nb Based)

[0446] With respect to the cross sections of the particles of the metal powders for powder metallurgy of the respective sample Nos. shown in Table 13, the crystal structure was evaluated by TEM.

[0447] As a result, in all the metal powders for powder metallurgy corresponding to Example, the average number of the Fe-based alloy crystals was 1 or more and 5 or less. Further, in all the metal powders for powder metallurgy corresponding to Example, the circle equivalent diameter of the Fe-based alloy crystal was 1% or more and 100% or less the circle equivalent diameter of the particle.

[0448] On the other hand, in all the metal powders for powder metallurgy corresponding to Comparative Example, the average number of the Fe-based alloy crystals was 6 or more.

15. Evaluation of Sintered Body (Y—Nb Based)

15.1 Evaluation of Relative Density

[0449] With respect to the sintered bodies of the respective sample Nos. shown in Table 13, the sintered density was measured in accordance with the method for measuring the density of sintered metal materials specified in JIS Z 2501 (2000), and also the relative density of each sintered body was calculated with reference to the true density of the metal powder for powder metallurgy used for producing each sintered body.

[0450] The calculation results are shown in Table 14.

15.2 Evaluation of Hardness

[0451] With respect to the sintered bodies of the respective sample Nos. shown in Table 13, the Vickers hardness was measured in accordance with the Vickers hardness test method specified in JIS Z 2244 (2009).

[0452] Then, the measured hardness was evaluated according to the evaluation criteria described in 3.2.

[0453] The evaluation results are shown in Table 14.

15.3 Evaluation of Tensile Strength, 0.2% Proof Stress, and Elongation

[0454] With respect to the sintered bodies of the respective sample Nos. shown in Table 13, the tensile strength, 0.2% proof stress, and elongation were measured in accordance with the metal material tensile test method specified in JIS Z 2241 (2011).

[0455] Then, the measured values of the physical properties were evaluated according to the above-mentioned evaluation criteria described in 3.3.

[0456] The evaluation results are shown in Table 14.

15.4 Evaluation of Fatigue Strength

[0457] With respect to the sintered bodies of the respective sample Nos. shown in Table 13, the fatigue strength was measured in the same manner as in 3.4.

[0458] Then, the measured fatigue strength was evaluated according to the evaluation criteria described in 3.4.

[0459] The evaluation results are shown in Table 14.

TABLE 14

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 133	Example	4.37	99.0	A	A	A	A	A
No. 134	Example	5.81	98.3	A	B	B	B	B
No. 135	Example	3.31	98.4	A	B	B	B	B
No. 136	Example	9.68	98.1	A	B	B	B	C
No. 137	Example	4.65	98.6	A	B	B	B	B
No. 138	Example	13.78	97.8	A	B	B	B	B
No. 139	Example	3.64	98.9	A	A	A	A	B
No. 140	Example	2.05	97.9	A	B	B	C	C
No. 141	Comparative	4.58	94.6	F	E	E	D	D

TABLE 14-continued

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 142	Example Comparative Example	4.02	95.2	F	E	E	D	D
No. 143	Example Comparative Example	2.72	95.0	F	E	E	E	E
No. 144	Example Comparative Example	3.12	94.4	F	D	D	E	E
No. 145	Example Comparative Example	2.09	94.1	F	F	F	F	F

[0460] As apparent from Table 14, it was confirmed that the sintered bodies corresponding to Example each have a higher relative density than the sintered bodies corresponding to Comparative Example. It was also confirmed that there is a significant difference in properties such as tensile strength, 0.2% proof stress, elongation, and fatigue strength between the sintered bodies corresponding to Example and the sintered bodies corresponding to Comparative Example.

16. Production of Sintered Body (V—Nb Based)

Sample Nos. 146 to 158

[0461] Sintered bodies were obtained in the same manner as the method for producing the sintered body of sample No. 1 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 15, respectively.

TABLE 15

Sample No.	—	Metal powder for powder metallurgy: Alloy composition: Cr mass %	C mass %	Si mass %	E1 (V) mass %	E2 (Nb) mass %	Mn mass %	Ni mass %	Cu mass %	O mass %	Fe mass %	E1/E2 —	E1 + E2 mass %	(E2)/Si —	(E2)/C —	Mn + Ni mass %	Remarks —
No. 146	Example	12.88	0.92	0.74	0.06	0.09	0.10	0.17	<0.01	0.26	remainder	0.67	0.15	0.20	0.16	0.27	
No. 147	Example	14.35	0.34	0.56	0.09	0.06	0.18	0.12	<0.01	0.24	remainder	1.50	0.15	0.27	0.44	0.30	
No. 148	Example	11.38	1.09	0.85	0.07	0.15	0.11	0.08	<0.01	0.26	remainder	0.47	0.22	0.26	0.20	0.19	
No. 149	Example	12.91	0.74	0.78	0.03	0.06	1.11	0.48	<0.01	0.45	remainder	0.50	0.09	0.12	0.12	1.59	
No. 150	Example	12.63	0.81	0.44	0.02	0.05	0.35	0.34	<0.01	0.39	remainder	0.40	0.07	0.16	0.09	0.69	
No. 151	Example	13.09	1.03	0.81	0.03	0.03	0.58	0.17	<0.01	0.28	remainder	1.00	0.06	0.07	0.06	0.75	
No. 152	Example	14.51	0.44	0.76	0.11	0.12	0.15	0.09	<0.01	0.39	remainder	0.92	0.23	0.30	0.52	0.24	
No. 153	Example	12.74	0.74	0.75	0.39	0.29	0.11	0.07	<0.01	0.29	remainder	1.34	0.68	0.91	0.92	0.18	
No. 154	Comparative Example	12.65	0.97	0.91	0.00	0.11	0.18	0.14	<0.01	0.39	remainder	0.00	0.11	0.12	0.11	0.32	
No. 155	Comparative Example	12.89	0.73	0.76	0.10	0.00	0.17	0.12	<0.01	0.41	remainder	—	0.10	0.13	0.14	0.29	
No. 156	Comparative Example	13.35	0.39	0.46	0.77	0.11	0.15	0.07	<0.01	0.25	remainder	7.00	0.88	1.91	2.26	0.22	
No. 157	Comparative Example	13.62	0.63	0.38	0.07	0.81	0.08	0.21	<0.01	0.41	remainder	0.09	0.88	2.32	1.40	0.29	
No. 158	Comparative Example	13.56	0.96	0.78	0.00	0.00	0.15	0.08	<0.01	0.36	remainder	—	0.00	0.00	0.00	0.23	

[0462] In Table 15, among the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0463] Each sintered body contained very small amounts of impurities, but the description thereof in Table 15 is omitted.

17. Evaluation of Metal Powder (V—Nb Based)

[0464] With respect to the cross sections of the particles of the metal powders for powder metallurgy of the respective sample Nos. shown in Table 15, the crystal structure was evaluated by TEM.

[0465] As a result, in all the metal powders for powder metallurgy corresponding to Example, the average number of the Fe-based alloy crystals was 1 or more and 5 or less. Further, in all the metal powders for powder metallurgy corresponding to Example, the circle equivalent diameter of the Fe-based alloy crystal was 1% or more and 100% or less the circle equivalent diameter of the particle.

[0466] On the other hand, in all the metal powders for powder metallurgy corresponding to Comparative Example, the average number of the Fe-based alloy crystals was 6 or more.

18. Evaluation of Sintered Body (V—Nb Based)

18.1 Evaluation of Relative Density

[0467] With respect to the sintered bodies of the respective sample Nos. shown in Table 15, the sintered density was measured in accordance with the method for measuring the density of sintered metal materials specified in JIS Z 2501 (2000), and also the relative density of each sintered body was calculated with reference to the true density of the metal powder for powder metallurgy used for producing each sintered body.

[0468] The calculation results are shown in Table 16.

18.2 Evaluation of Hardness

[0469] With respect to the sintered bodies of the respective sample Nos. shown in Table 15, the Vickers hardness was measured in accordance with the Vickers hardness test method specified in JIS Z 2244 (2009).

[0470] Then, the measured hardness was evaluated according to the evaluation criteria described in 3.2.

[0471] The evaluation results are shown in Table 16.

18.3 Evaluation of Tensile Strength, 0.2% Proof Stress, and Elongation

[0472] With respect to the sintered bodies of the respective sample Nos. shown in Table 15, the tensile strength, 0.2% proof stress, and elongation were measured in accordance with the metal material tensile test method specified in JIS Z 2241 (2011).

[0473] Then, the measured values of the physical properties were evaluated according to the above-mentioned evaluation criteria described in 3.3.

[0474] The evaluation results are shown in Table 16.

18.4 Evaluation of Fatigue Strength

[0475] With respect to the sintered bodies of the respective sample Nos. shown in Table 15, the fatigue strength was measured in the same manner as in 3.4.

[0476] Then, the measured fatigue strength was evaluated according to the evaluation criteria described in 3.4.

[0477] The evaluation results are shown in Table 16.

TABLE 16

		Metal powder	Evaluation results of sintered body					
Sample No.	—	Average particle diameter μm	Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 146	Example	4.42	98.8	A	A	A	A	A
No. 147	Example	5.96	98.1	A	B	B	B	B
No. 148	Example	3.21	98.2	A	B	B	B	B
No. 149	Example	10.25	97.9	A	B	B	C	C
No. 150	Example	4.78	98.4	A	B	B	B	B
No. 151	Example	14.26	97.7	A	B	B	B	C
No. 152	Example	3.55	98.7	A	A	A	B	B
No. 153	Example	2.18	97.7	A	B	B	B	C
No. 154	Comparative Example	4.87	94.5	F	E	E	D	D
No. 155	Comparative Example	3.89	95.1	F	F	F	E	E
No. 156	Comparative Example	2.63	94.8	F	F	F	E	E
No. 157	Comparative Example	3.08	95.2	F	E	E	D	D
No. 158	Comparative Example	2.15	94.1	F	F	F	E	E

[0478] As apparent from Table 16, it was confirmed that the sintered bodies corresponding to Example each have a higher relative density than the sintered bodies corresponding to Comparative Example. It was also confirmed that there is a significant difference in properties such as tensile strength, 0.2% proof stress, elongation, and fatigue strength between the sintered bodies corresponding to Example and the sintered bodies corresponding to Comparative Example.

19. Production of Sintered Body (Ti—Zr Based)

Sample Nos. 159 to 171

[0479] Sintered bodies were obtained in the same manner as the method for producing the sintered body of sample No. 1 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 17, respectively.

TABLE 17

		Metal powder for powder metallurgy															
		Alloy composition												(E1 +	(E1 +		
Sample No.	—	Cr	C	Si	E1 (Ti)	E2 (Zr)	Mn	Ni	Cu	O	Fe	E1/ E2	E1 + E2	E2)/ Si	E2)/ C	Mn + Ni	Remarks
		mass %										—	mass %	—	—	mass %	—
No. 159	Example	12.86	0.89	0.72	0.07	0.08	0.09	0.16	<0.01	0.27	remainder	0.88	0.15	0.21	0.17	0.25	
No. 160	Example	14.41	0.27	0.52	0.08	0.06	0.19	0.11	<0.01	0.19	remainder	1.33	0.14	0.27	0.52	0.30	
No. 161	Example	11.35	1.11	0.86	0.06	0.16	0.12	0.08	<0.01	0.25	remainder	0.38	0.22	0.26	0.20	0.20	
No. 162	Example	12.89	0.73	0.77	0.03	0.05	1.13	0.43	<0.01	0.46	remainder	0.60	0.08	0.10	0.11	1.56	
No. 163	Example	12.61	0.79	0.43	0.02	0.04	0.33	0.29	<0.01	0.38	remainder	0.50	0.06	0.14	0.08	0.62	
No. 164	Example	13.11	1.01	0.80	0.04	0.04	0.56	0.17	<0.01	0.28	remainder	1.00	0.08	0.10	0.08	0.73	
No. 165	Example	14.53	0.45	0.77	0.11	0.20	0.15	0.09	<0.01	0.41	remainder	0.55	0.31	0.40	0.69	0.24	
No. 166	Example	12.76	0.73	0.76	0.41	0.28	0.13	0.09	<0.01	0.31	remainder	1.46	0.69	0.91	0.95	0.22	
No. 167	Comparative Example	12.68	0.98	0.93	0.00	0.12	0.19	0.15	<0.01	0.37	remainder	0.00	0.12	0.13	0.12	0.34	
No. 168	Comparative Example	12.86	0.72	0.77	0.11	0.00	0.18	0.13	<0.01	0.42	remainder	—	0.11	0.14	0.15	0.31	
No. 169	Comparative Example	13.42	0.38	0.47	0.79	0.10	0.16	0.08	<0.01	0.26	remainder	7.90	0.88	1.89	2.34	0.24	
No. 170	Comparative Example	13.65	0.64	0.37	0.08	0.81	0.09	0.23	<0.01	0.43	remainder	0.10	0.89	2.41	1.39	0.32	
No. 171	Comparative Example	13.57	0.97	0.79	0.00	0.00	0.16	0.09	<0.01	0.41	remainder	—	0.00	0.00	0.00	0.25	

[0480] In Table 17, among the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0481] Each sintered body contained very small amounts of impurities, but the description thereof in Table 17 is omitted.

20. Evaluation of Metal Powder (Ti—Zr Based)

[0482] With respect to the cross sections of the particles of the metal powders for powder metallurgy of the respective sample Nos. shown in Table 17, the crystal structure was evaluated by TEM.

[0483] As a result, in all the metal powders for powder metallurgy corresponding to Example, the average number of the Fe-based alloy crystals was 1 or more and 5 or less. Further, in all the metal powders for powder metallurgy corresponding to Example, the circle equivalent diameter of the Fe-based alloy crystal was 1% or more and 100% or less the circle equivalent diameter of the particle.

[0484] On the other hand, in all the metal powders for powder metallurgy corresponding to Comparative Example, the average number of the Fe-based alloy crystals was 6 or more.

21. Evaluation of Sintered Body (Ti—Zr Based)

21.1 Evaluation of Relative Density

[0485] With respect to the sintered bodies of the respective sample Nos. shown in Table 17, the sintered density was measured in accordance with the method for measuring the density of sintered metal materials specified in JIS Z 2501 (2000), and also the relative density of each sintered body was calculated with reference to the true density of the metal powder for powder metallurgy used for producing each sintered body.

[0486] The calculation results are shown in Table 18.

21.2 Evaluation of Hardness

[0487] With respect to the sintered bodies of the respective sample Nos. shown in Table 17, the Vickers hardness was measured in accordance with the Vickers hardness test method specified in JIS Z 2244 (2009).

[0488] Then, the measured hardness was evaluated according to the evaluation criteria described in 3.2.

[0489] The evaluation results are shown in Table 18.

21.3 Evaluation of Tensile Strength, 0.2% Proof Stress, and Elongation

[0490] With respect to the sintered bodies of the respective sample Nos. shown in Table 17, the tensile strength, 0.2% proof stress, and elongation were measured in accordance

with the metal material tensile test method specified in JIS Z 2241 (2011).

[0491] Then, the measured values of the physical properties were evaluated according to the above-mentioned evaluation criteria described in 3.3.

[0492] The evaluation results are shown in Table 18.

21.4 Evaluation of Fatigue Strength

[0493] With respect to the sintered bodies of the respective sample Nos. shown in Table 17, the fatigue strength was measured in the same manner as in 3.4.

[0494] Then, the measured fatigue strength was evaluated according to the evaluation criteria described in 3.4.

[0495] The evaluation results are shown in Table 18.

TABLE 18

		Metal powder	Evaluation results of sintered body					
Sample No.	—	Average particle diameter μm	Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 159	Example	4.51	98.8	A	A	A	A	A
No. 160	Example	6.05	98.4	A	A	A	B	B
No. 161	Example	3.16	98.3	A	A	A	A	B
No. 162	Example	10.37	98.1	A	B	B	B	C
No. 163	Example	4.82	98.5	A	B	B	B	B
No. 164	Example	14.15	98.2	A	B	B	B	B
No. 165	Example	3.64	98.9	A	A	A	B	A
No. 166	Example	2.11	98.2	A	B	B	C	C
No. 167	Comparative Example	4.92	94.7	F	C	C	C	D
No. 168	Comparative Example	3.96	95.3	F	D	D	D	E
No. 169	Comparative Example	2.54	95.0	F	F	F	D	D
No. 170	Comparative Example	3.11	95.3	F	E	E	E	E
No. 171	Comparative Example	2.24	94.3	F	F	F	F	F

[0496] As apparent from Table 18, it was confirmed that the sintered bodies corresponding to Example each have a higher relative density than the sintered bodies corresponding to Comparative Example. It was also confirmed that there is a significant difference in properties such as tensile strength, 0.2% proof stress, elongation, and fatigue strength between the sintered bodies corresponding to Example and the sintered bodies corresponding to Comparative Example.

22. Production of Sintered Body (Zr—Ta Based)

Sample Nos. 172 to 184

[0497] Sintered bodies were obtained in the same manner as the method for producing the sintered body of sample No. 1 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 19, respectively.

TABLE 19

		Metal powder for powder metallurgy															
		Alloy composition															
Sample No.	—	Cr	C	Si	E1 (Zr)	E2 (Ta)	Mn	Ni	Cu	O	Fe	E1/ E2 —	E1 + E2 mass %	(E1 + E2)/ Si —	(E1 + E2)/ C —	Mn + Ni mass %	Remarks —
		mass %															
No. 172	Example	12.83	0.87	0.73	0.07	0.12	0.11	0.17	<0.01	0.29	remainder	0.58	0.19	0.26	0.22	0.28	
No. 173	Example	14.43	0.28	0.54	0.06	0.06	0.22	0.12	<0.01	0.25	remainder	1.00	0.12	0.22	0.43	0.34	

TABLE 19-continued

		Metal powder for powder metallurgy																
		Alloy composition																
Sample No.	—	Cr	C	Si	E1 (Zr)	E2 (Ta)	Mn	Ni	Cu	O	Fe	E1/ E2	E1 + E2	(E1 + E2)/ Si	(E1 + E2)/ C	Mn + Ni	Re- marks	
		mass %										—	mass %	—	—	mass %	—	
No. 174	Example	11.33	1.09	0.84	0.06	0.16	0.08	0.12	<0.01	0.37	remainder	0.38	0.22	0.26	0.20	0.20		
No. 175	Example	12.86	0.71	0.78	0.03	0.06	1.15	0.39	<0.01	0.45	remainder	0.50	0.09	0.12	0.13	1.54		
No. 176	Example	12.59	0.81	0.45	0.02	0.10	0.34	0.28	<0.01	0.37	remainder	0.20	0.12	0.27	0.15	0.62		
No. 177	Example	13.09	1.05	0.81	0.05	0.04	0.57	0.21	<0.01	0.34	remainder	1.25	0.09	0.11	0.09	0.78		
No. 178	Example	14.55	0.43	0.78	0.12	0.22	0.16	0.10	<0.01	0.39	remainder	0.55	0.34	0.44	0.79	0.26		
No. 179	Example	12.74	0.72	0.77	0.28	0.47	0.15	0.10	<0.01	0.29	remainder	0.66	0.75	0.97	1.04	0.25		
No. 180	Comparative Example	12.66	0.97	0.92	0.00	0.11	0.21	0.16	<0.01	0.36	remainder	0.00	0.11	0.12	0.11	0.37		
No. 181	Comparative Example	12.85	0.71	0.76	0.10	0.00	0.19	0.12	<0.01	0.39	remainder	—	0.10	0.13	0.14	0.31		
No. 182	Comparative Example	13.45	0.36	0.45	0.81	0.09	0.15	0.10	<0.01	0.27	remainder	9.00	0.90	2.00	2.50	0.25		
No. 183	Comparative Example	13.66	0.63	0.38	0.09	0.82	0.10	0.21	<0.01	0.44	remainder	0.11	0.91	2.39	1.44	0.31		
No. 184	Comparative Example	13.55	0.96	0.76	0.00	0.00	0.15	0.10	<0.01	0.39	remainder	—	0.00	0.00	0.00	0.25		

[0498] In Table 19, among the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0499] Each sintered body contained very small amounts of impurities, but the description thereof in Table 19 is omitted.

23. Evaluation of Metal Powder (Zr—Ta Based)

[0500] With respect to the cross sections of the particles of the metal powders for powder metallurgy of the respective sample Nos. shown in Table 19, the crystal structure was evaluated by TEM.

[0501] As a result, in all the metal powders for powder metallurgy corresponding to Example, the average number of the Fe-based alloy crystals was 1 or more and 5 or less. Further, in all the metal powders for powder metallurgy corresponding to Example, the circle equivalent diameter of the Fe-based alloy crystal was 1% or more and 100% or less the circle equivalent diameter of the particle.

[0502] On the other hand, in all the metal powders for powder metallurgy corresponding to Comparative Example, the average number of the Fe-based alloy crystals was 6 or more.

24. Evaluation of Sintered Body (Zr—Ta Based)

24.1 Evaluation of Relative Density

[0503] With respect to the sintered bodies of the respective sample Nos. shown in Table 19, the sintered density was measured in accordance with the method for measuring the density of sintered metal materials specified in JIS Z 2501 (2000), and also the relative density of each sintered body was calculated with reference to the true density of the metal powder for powder metallurgy used for producing each sintered body.

[0504] The calculation results are shown in Table 20.

24.2 Evaluation of Hardness

[0505] With respect to the sintered bodies of the respective sample Nos. shown in Table 19, the Vickers hardness was measured in accordance with the Vickers hardness test method specified in JIS Z 2244 (2009).

[0506] Then, the measured hardness was evaluated according to the evaluation criteria described in 3.2.

[0507] The evaluation results are shown in Table 20.

24.3 Evaluation of Tensile Strength, 0.2% Proof Stress, and Elongation

[0508] With respect to the sintered bodies of the respective sample Nos. shown in Table 19, the tensile strength, 0.2% proof stress, and elongation were measured in accordance with the metal material tensile test method specified in JIS Z 2241 (2011).

[0509] Then, the measured values of the physical properties were evaluated according to the above-mentioned evaluation criteria described in 3.3.

[0510] The evaluation results are shown in Table 20.

24.4 Evaluation of Fatigue Strength

[0511] With respect to the sintered bodies of the respective sample Nos. shown in Table 19, the fatigue strength was measured in the same manner as in 3.4.

[0512] Then, the measured fatigue strength was evaluated according to the evaluation criteria described in 3.4.

[0513] The evaluation results are shown in Table 20.

TABLE 20

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 172	Example	4.22	98.8	A	A	A	A	A
No. 173	Example	6.29	98.5	A	A	A	B	B
No. 174	Example	3.25	98.6	A	A	A	A	B
No. 175	Example	9.86	98.2	A	B	B	B	B
No. 176	Example	5.23	98.6	A	A	A	B	A
No. 177	Example	14.39	98.4	A	B	B	A	A
No. 178	Example	3.75	98.7	A	A	A	B	A
No. 179	Example	2.08	98.3	A	B	B	C	C
No. 180	Comparative Example	4.89	94.6	F	E	E	E	E
No. 181	Comparative Example	4.21	95.2	A	C	C	D	D
No. 182	Comparative Example	2.63	95.1	F	D	D	E	E
No. 183	Comparative Example	3.08	94.8	F	F	F	E	E
No. 184	Comparative Example	2.39	94.2	F	F	F	F	F

[0514] As apparent from Table 20, it was confirmed that the sintered bodies corresponding to Example each have a higher relative density than the sintered bodies corresponding to Comparative Example. It was also confirmed that there is a significant difference in properties such as tensile strength, 0.2% proof stress, elongation, and fatigue strength between the sintered bodies corresponding to Example and the sintered bodies corresponding to Comparative Example.

25. Production of Sintered Body (Zr—V Based)

Sample Nos. 185 to 197

[0515] Sintered bodies were obtained in the same manner as the method for producing the sintered body of sample No. 1 except that the composition and the like of the metal powder for powder metallurgy were changed as shown in Table 21, respectively.

TABLE 21

		Metal powder for powder metallurgy: Alloy composition: Cr	C	Si	E1 (Zr)	E2 (V)	Mn	Ni	Cu	O	Fe	E1/E2	E1 + E2	(E1 + E2)/Si	(E1 + E2)/C	Mn + Ni	Remarks
Sample No.	—	mass %										—	mass %	—	—	mass %	—
No. 185	Example	12.81	0.86	0.72	0.12	0.07	0.10	0.18	<0.01	0.28	remainder	1.71	0.19	0.26	0.22	0.28	
No. 186	Example	14.44	0.27	0.55	0.07	0.11	0.19	0.12	<0.01	0.27	remainder	0.64	0.18	0.33	0.67	0.31	
No. 187	Example	11.28	1.11	0.83	0.18	0.07	0.08	0.11	<0.01	0.38	remainder	2.57	0.25	0.30	0.23	0.19	
No. 188	Example	12.88	0.72	0.79	0.06	0.02	1.15	0.36	<0.01	0.43	remainder	3.00	0.08	0.10	0.11	1.51	
No. 189	Example	12.57	0.79	0.43	0.04	0.02	0.34	0.05	<0.01	0.39	remainder	2.00	0.06	0.14	0.08	0.39	
No. 190	Example	13.11	1.02	0.90	0.05	0.04	0.56	0.21	<0.01	0.32	remainder	1.25	0.09	0.10	0.09	0.77	
No. 191	Example	14.56	0.42	0.76	0.12	0.16	0.16	0.12	<0.01	0.36	remainder	0.75	0.28	0.37	0.67	0.28	
No. 192	Example	12.72	0.71	0.78	0.27	0.45	0.12	0.09	<0.01	0.27	remainder	0.60	0.72	0.92	1.01	0.21	
No. 193	Comparative Example	12.64	0.95	0.91	0.00	0.12	0.19	0.15	<0.01	0.34	remainder	0.00	0.12	0.13	0.13	0.34	
No. 194	Comparative Example	12.87	0.72	0.77	0.10	0.00	0.21	0.11	<0.01	0.37	remainder	—	0.10	0.13	0.14	0.32	

TABLE 21-continued

Sample No.	—	Metal powder for powder metallurgy: Alloy composition: Cr mass %	C mass %	Si mass %	E1 (Zr) mass %	E2 (V) mass %	Mn mass %	Ni mass %	Cu mass %	O mass %	Fe mass %	E1/E2 —	E1 + E2 mass %	(E1 + E2)/Si —	(E1 + E2)/C —	Mn + Ni mass %	Remarks —
No. 195	Comparative Example	13.48	0.34	0.44	0.81	0.11	0.16	0.12	<0.01	0.29	remainder	7.36	0.92	2.09	2.71	0.28	
No. 196	Comparative Example	13.68	0.64	0.35	0.09	0.82	0.15	0.25	<0.01	0.44	remainder	0.11	0.91	2.60	1.42	0.40	
No. 197	Comparative Example	13.57	0.92	0.77	0.00	0.00	0.16	0.12	<0.01	0.38	remainder	—	0.00	0.00	0.00	0.28	

[0516] In Table 21, among the sintered bodies of the respective sample Nos., those corresponding to the invention are indicated by "Example", and those not corresponding to the invention are indicated by "Comparative Example".

[0517] Each sintered body contained very small amounts of impurities, but the description thereof in Table 21 is omitted.

26. Evaluation of Metal Powder (Zr—V Based)

[0518] With respect to the cross sections of the particles of the metal powders for powder metallurgy of the respective sample Nos. shown in Table 21, the crystal structure was evaluated by TEM.

[0519] As a result, in all the metal powders for powder metallurgy corresponding to Example, the average number of the Fe-based alloy crystals was 1 or more and 5 or less. Further, in all the metal powders for powder metallurgy corresponding to Example, the circle equivalent diameter of the Fe-based alloy crystal was 1% or more and 100% or less the circle equivalent diameter of the particle.

[0520] On the other hand, in all the metal powders for powder metallurgy corresponding to Comparative Example, the average number of the Fe-based alloy crystals was 6 or more.

27. Evaluation of Sintered Body (Zr—V Based)

27.1 Evaluation of Relative Density

[0521] With respect to the sintered bodies of the respective sample Nos. shown in Table 21, the sintered density was measured in accordance with the method for measuring the density of sintered metal materials specified in JIS Z 2501 (2000), and also the relative density of each sintered body was calculated with reference to the true density of the metal powder for powder metallurgy used for producing each sintered body.

[0522] The calculation results are shown in Table 22.

27.2 Evaluation of Hardness

[0523] With respect to the sintered bodies of the respective sample Nos. shown in Table 21, the Vickers hardness was measured in accordance with the Vickers hardness test method specified in JIS Z 2244 (2009).

[0524] Then, the measured hardness was evaluated according to the evaluation criteria described in 3.2.

[0525] The evaluation results are shown in Table 22.

27.3 Evaluation of Tensile Strength, 0.2% Proof Stress, and Elongation

[0526] With respect to the sintered bodies of the respective sample Nos. shown in Table 21, the tensile strength, 0.2% proof stress, and elongation were measured in accordance with the metal material tensile test method specified in JIS Z 2241 (2011).

[0527] Then, the measured values of the physical properties were evaluated according to the above-mentioned evaluation criteria described in 3.3.

[0528] The evaluation results are shown in Table 22.

27.4 Evaluation of Fatigue Strength

[0529] With respect to the sintered bodies of the respective sample Nos. shown in Table 21, the fatigue strength was measured in the same manner as in 3.4.

[0530] Then, the measured fatigue strength was evaluated according to the evaluation criteria described in 3.4.

[0531] The evaluation results are shown in Table 22.

TABLE 22

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 185	Example	4.51	99.2	A	A	A	A	A
No. 186	Example	6.78	98.9	A	A	A	B	B
No. 187	Example	3.24	99.1	A	A	A	B	B
No. 188	Example	9.87	98.6	A	A	B	B	B

TABLE 22-continued

Sample No.	—	Metal powder: Average particle diameter μm	Evaluation results of sintered body: Relative density %	Vickers hardness —	Tensile strength —	0.2% proof stress —	Elongation —	Fatigue strength —
No. 189	Example	5.02	98.8	A	A	B	B	B
No. 190	Example	14.39	98.7	A	A	B	B	B
No. 191	Example	3.82	99.0	A	A	A	A	B
No. 192	Example	2.09	98.5	A	B	B	B	C
No. 193	Comparative Example	4.85	95.0	F	D	D	D	D
No. 194	Comparative Example	4.16	95.8	A	C	C	D	D
No. 195	Comparative Example	2.78	95.2	F	F	F	E	E
No. 196	Comparative Example	3.11	95.0	F	F	F	F	F
No. 197	Comparative Example	2.28	94.5	F	F	F	F	F

[0532] As apparent from Table 22, it was confirmed that the sintered bodies corresponding to Example each have a higher relative density than the sintered bodies corresponding to Comparative Example. It was also confirmed that there is a significant difference in properties such as tensile strength, 0.2% proof stress, elongation, and fatigue strength between the sintered bodies corresponding to Example and the sintered bodies corresponding to Comparative Example.

28. Evaluation of Specularity of Sintered Body

28.1 Evaluation of Porosity Near Surface and Inside

[0533] First, each of the sintered bodies of the respective sample Nos. shown in Table 23 was cut and the cross section was polished.

[0534] Then, a porosity A1 near the surface of the sintered body and a porosity A2 inside the sintered body were calculated and also A2-A1 was calculated.

[0535] The above calculation results are shown in Table 23.

28.2 Evaluation of Specular Gloss

[0536] First, each of the sintered bodies of the respective sample Nos. shown in Table 23 was subjected to a barrel polishing treatment.

[0537] Then, the specular gloss of the sintered body was measured in accordance with the method for measuring the specular gloss specified in JIS Z 8741 (1997). The incident angle of light with respect to the surface of the sintered body was set to 60°, and as a reference plane for calculating the specular gloss, a glass having a specular gloss of 90 and a refractive index of 1.500 was used. Then, the measured specular gloss was evaluated according to the following evaluation criteria.

Evaluation Criteria for Specular Gloss

[0538] A: The specularity of the surface is very high (the specular gloss is 200 or more).

[0539] B: The specularity of the surface is high (the specular gloss is 150 or more and less than 200).

[0540] C: The specularity of the surface is slightly high (the specular gloss is 100 or more and less than 150).

[0541] D: The specularity of the surface is slightly low (the specular gloss is 60 or more and less than 100).

[0542] E: The specularity of the surface is low (the specular gloss is 30 or more and less than 60).

[0543] F: The specularity of the surface is very low (the specular gloss is less than 30).

[0544] The above evaluation results are shown in Table 23.

TABLE 23

Sample No.	Example/ Comparative Example	Alloy composition: E1	E2	Evaluation results: A2-A1 [%]	Specular gloss
1	Example	Zr	Nb	0.8	A
31	Comparative Example			0.1	E
85	Example	Hf	Nb	0.8	A
101	Comparative Example			0.1	E
106	Example	Ti	Nb	1.1	A
115	Comparative Example			0.2	E
120	Example	Nb	Ta	0.4	C
128	Comparative Example			0.1	E
133	Example	Y	Nb	1.2	A
142	Comparative Example			0.1	E
146	Example	V	Nb	0.7	C
155	Comparative Example			0.2	E
159	Example	Ti	Zr	0.4	C
169	Comparative Example			0.1	E

TABLE 23-continued

Sample No.	Example/ Comparative Example	Alloy composition E1	Alloy composition E2	Evaluation results A2-A1 [%]	Evaluation results Specular gloss
172	Example	Zr	Ta	0.6	B
182	Comparative Example			0.1	E
185	Example	Zr	V	0.6	B
195	Comparative Example			0.1	E

[0545] As apparent from Table 23, it was confirmed that the sintered bodies corresponding to Example each have a higher specular gloss than the sintered bodies corresponding to Comparative Example. This is considered to be because the porosity near the surface of the sintered body is low, and therefore, light scattering is suppressed, however, the ratio of regular reflection is increased.

What is claimed is:

1. A metal powder for powder metallurgy, comprising particles, which contain

Fe as a principal component,

Cr in a proportion of 10% by mass or more and 30% by mass or less,

C in a proportion of 0.1% by mass or more and 2% by mass or less, and

Si in a proportion of 0.2% by mass or more and 1.5% by mass or less, and in which

when one element selected from the group consisting of Ti, V, Y, Zr, Nb, Hf, and Ta is defined as a first element, and one element selected from the group consisting of Ti, V, Y, Zr, Nb, Hf, and Ta, and having a higher group number in the periodic table than that of the first element or having the same group number in the periodic table as that of the first element and a higher period number in the periodic table than that of the first element is defined as a second element,

the first element is contained in a proportion of 0.01% by mass or more and 0.5% by mass or less, and

the second element is contained in a proportion of 0.01% by mass or more and 0.5% by mass or less, wherein

the number of crystals in the cross section of the particle is 1 or more and 5 or less on average.

2. The metal powder for powder metallurgy according to claim **1**, wherein

the crystal contains Fe as a principal component, and

the particle further includes a region, which has a smaller volume than the crystal, and in which the ratio of the content of Si to the content of Fe is higher than in the crystal.

3. The metal powder for powder metallurgy according to claim **1**, wherein in the cross section of the particle, the circle equivalent diameter of the crystal is 1% or more and 100% or less the circle equivalent diameter of the particle.

4. The metal powder for powder metallurgy according to claim **1**, wherein the crystal has a martensite crystal structure.

5. A compound, comprising the metal powder for powder metallurgy according to claim **1** and a binder which binds the particles of the metal powder for powder metallurgy to one another.

6. A compound, comprising the metal powder for powder metallurgy according to claim **2** and a binder which binds the particles of the metal powder for powder metallurgy to one another.

7. A compound, comprising the metal powder for powder metallurgy according to claim **3** and a binder which binds the particles of the metal powder for powder metallurgy to one another.

8. A compound, comprising the metal powder for powder metallurgy according to claim **4** and a binder which binds the particles of the metal powder for powder metallurgy to one another.

9. A granulated powder, wherein the granulated powder is obtained by granulating the metal powder for powder metallurgy according to claim **1**.

10. A granulated powder, wherein the granulated powder is obtained by granulating the metal powder for powder metallurgy according to claim **2**.

11. A granulated powder, wherein the granulated powder is obtained by granulating the metal powder for powder metallurgy according to claim **3**.

12. A granulated powder, wherein the granulated powder is obtained by granulating the metal powder for powder metallurgy according to claim **4**.

13. A sintered body, wherein the sintered body is produced by sintering the metal powder for powder metallurgy according to claim **1**.

14. A sintered body, wherein the sintered body is produced by sintering the metal powder for powder metallurgy according to claim **2**.

15. A sintered body, wherein the sintered body is produced by sintering the metal powder for powder metallurgy according to claim **3**.

16. A sintered body, wherein the sintered body is produced by sintering the metal powder for powder metallurgy according to claim **4**.

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