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**(54) MATERIAL FOR NUCLEAR FUSION REACTOR EXCELLENT IN HIGH TEMPERATURE CHARACTERISTICS COMPRISING BERYLLIUM INTERMETALLIC COMPOUND**

MATERIAL FÜR EINEN KERNFUSIONSREAKTOR MIT AUSGEZEICHNETEN HOCHTEMPERATUREIGENSCHAFTEN MIT INTERMETALLISCHER BERYLLIUMZUSAMMENSETZUNG

MATERIAU POUR UN REACTEUR DE FUSION NUCLEAIRE PRESENTANT D'EXCELLENTE CARACTERISTIQUES A DES TEMPERATURES ELEVEES ET COMPRENANT UN COMPOSE INTERMETALLIQUE DE BERYLLIUM

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**Description****TECHNICAL FIELD**

5 [0001] The present invention relates to a material including a beryllium intermetallic compound applied to nuclear fusion reactors and more specifically relates to a material including a beryllium intermetallic compound applied to blankets and plasma facing members of nuclear fusion reactors, which are exposed to neutrons and heat generated by plasma in the nuclear fusion reactors.

**BACKGROUND ART**

15 [0002] A Tokamak nuclear fusion reactor generates ring-like plasma so as to produce nuclear fusion reaction therein by means of electromagnetic coils arranged like a circumference. The ring-like plasma radiates neutrons and radiant heat and hence blankets and plasma facing members are disposed so as to enclose the plasma. The blanket is essentially composed of neutron multiplier members for further breeding neutrons from the radiated neutrons, tritium multiplier members for breeding tritiums from the multiplied neutrons and cooling water circulation system for cooling these members so as to extract heat. The plasma facing members are disposed within the blankets so as to protect the blankets from the plasma.

20 [0003] To the blankets and the plasma facing members, it is necessary to apply materials of reduced susceptibility of swelling, which is defined as volumetric expansion results from bubbles generated in the materials caused by exposure to radiation. Furthermore, the materials are required not to absorb a large amount of tritiums so as to effectively collect the tritiums.

25 [0004] Among materials for the blankets, the material applied to the neutron multiplier members is required to have a large reaction cross section with respect to the neutrons. Beryllium formed in small pebbles has been conventionally employed.

[0005] As the material applied to the plasma facing member, it is necessary to be less susceptible of sputtering erosion by the plasma and has small radiation loss in a case where contamination into the plasma caused by the sputtering occurs. Tungsten, beryllium and carbon or carbon composite material has been hitherto under examination for application.

**DISCLOSURE OF INVENTION**

35 [0006] Beryllium has relatively excellent properties with respect to any of the aforementioned applications. Beryllium would not cause any trouble in a case where the temperature is below about 400 degree C and the exposure to the neutrons is below about 3000 appmHe, but might give rise to risks of hydrogen generation and consequent hydrogen explosion led from an oxidation reaction by a high-temperature water vapor in a case where the temperature in use is beyond about 600 degree C and any accident such as breaking of cooling tubes is happened. Moreover, beryllium has a problem of reactivity with a stainless steel ISO-19N of which the blanket is made. Furthermore, there is a possibility that large swelling of beryllium leads to breaking of a vessel and such accidents. On the other hand, as the plasma facing material, beryllium is more susceptible of sputtering erosion than tungsten, carbon and carbon composite materials.

40 Therefore any material capable of use in higher temperature and less susceptible of sputtering erosion is expected.

[0007] The present invention is accomplished in view of the above problem and intended for providing a material for nuclear fusion reactors being capable of use in higher temperature and less susceptible of sputtering erosion.

45 [0008] The present inventors paid their attention to intermetallic compounds of beryllium with Ti, V, Zr, Nb, Ta, Mo, W or Y as also having the excellent properties of beryllium and additionally having a high-temperature property and being less susceptible of sputtering erosion. Such beryllium intermetallic compounds are generally brittle and hence uneasy to be machined and handled. The present inventors invented that brittleness of the beryllium intermetallic compounds can be overcome by means of dispersing the compounds in another metal or making composites with another intermetallic compounds and then reached to the present invention of the material practically applied to the nuclear fusion reactors.

50 [0009] According to a first aspect of the present invention, a material for a nuclear fusion reactor is an alloy including at least one beryllium intermetallic compound phase. The beryllium intermetallic compound phase preferably consists of a compound of Be with one or more elements selected from the group of Ti, V, Zr, Nb, Ta, Mo, W and Y. More preferably, a matrix phase thereof consists of one or more metals selected from the group of Be, Zr, Ti and V. Still preferably, a volumetric ratio of the beryllium intermetallic compound phase is 50 to 99 %. The material for the nuclear fusion reactor is preferably applied to a neutron multiplier material.

55 [0010] According to a second aspect of the present invention, a material for a nuclear fusion reactor consists **essentially** of one or more substances selected from the group of  $\text{Be}_{12}\text{M}$  or  $\text{Be}_{13}\text{M}$  and  $\text{Be}_{17}\text{M}_2$ ; or two or more substances selected from the groups of  $\text{Be}_{12}\text{M}$  or  $\text{Be}_{13}\text{M}$ ,  $\text{Be}_{17}\text{M}_2$ , **Be or M**, wherein M is a metal element selected from the group of Ti, V, Mo, W, Zr, Nb and Ta, and an average content x of M is in a range of  $2.0 \leq x \leq 15.0$  (at%), or preferably  $7.7 < x < 10.5$

(at%). The material for the nuclear fusion reactor consisting of beryllium intermetallic compounds is preferably applied to a nuclear multiplier material, and further applied to a plasma facing material as well.

**[0011]** Preferably, the material for the nuclear fusion reactor of any of the above aspects is produced by casting or sintering and a crystal particle size is no more than 50  $\mu\text{m}$ .

## BRIEF DESCRIPTION OF DRAWINGS

**[0012]** Fig. 1 shows a micro-metallograph of a neutron multiplier material according to a first embodiment of the present invention.

## BEST MODE FOR CARRYING OUT THE INVENTION

[FIRST EMBODIMENT]

**[0013]** A neutron multiplier material according to the present invention includes metallic phases interposed between the beryllium intermetallic compound phases so that the metallic phases adhere the beryllium intermetallic compound phases and accordingly whole body of the neutron multiplier material gets higher ductility, which leads to advantages of machinability and easiness of handling.

**[0014]** To the beryllium intermetallic compound phases of the present invention, compounds of beryllium with Ti, V, Zr, Nb, Ta, Mo, W or Y, listed below as examples, are specifically preferably adapted.

**[0015]**  $\text{Be}_{12}\text{Ti}$  (1550 degree C),  $\text{Be}_{17}\text{Ti}_2$  (1650 degree C),  $\text{Be}_{12}\text{V}$  (1700 degree C),  $\text{Be}_{13}\text{Zr}$  (1800 degree C),  $\text{Be}_{17}\text{Zr}_{12}$  (1600 degree C),  $\text{Be}_{12}\text{Nb}$  (1700 degree C),  $\text{Be}_{17}\text{Nb}_2$  (1800 degree C),  $\text{Be}_{12}\text{Ta}$  (1850 degree C),  $\text{Be}_{17}\text{Ta}_2$  (1970 degree C),  $\text{Be}_{12}\text{Mo}$  (1700 degree C),  $\text{Be}_{12}\text{W}$  (1750 degree C),  $\text{Be}_{22}\text{W}$  (1600 degree C),  $\text{Be}_{13}\text{Y}$  (1920 degree C), where the values put in parentheses respectively indicate melting points thereof.

**[0016]** Any of the aforementioned beryllium intermetallic compounds has a high melting point and high oxidation resistance so as to indicate excellent heat-resistance.

**[0017]** While such beryllium intermetallic compounds are slightly inferior in the neutron multiplying effect to metallic beryllium, tritium inventory and reactivity with structural members of the blanket are relatively lower. Particularly, anti-swelling property thereof is exceedingly good.

**[0018]** Moreover, to the metallic phase of the present invention, any metal selected from the group of Be, Zr, Ti and V is preferable. Because these metals effectively go around and fill gaps among the beryllium intermetallic compounds and hence efficiently increase ductility of the multiplier material including the beryllium intermetallic compounds as a whole.

**[0019]** Particularly, Be and Zr are further preferably applied to the metallic phase as having a neutron multiplying function as well.

**[0020]** Furthermore, a ratio of the beryllium intermetallic phase in such a neutron multiplying material is favorably set about 50 through 99 % in volumetric ratio.

**[0021]** Because, provided that the mixing ratio does not reach 50 vol%, reactivity with vapor and such and swelling are remarkably increased and, provided that the mixing ratio exceeds 99 vol%, the effect of increasing ductility by the metallic phase is decreased so that reduction of the machinability and the easiness of handling is unavoidable.

**[0022]** Size of pebbles of the neutron multiplier material according to the present invention is preferably set about 0.1 through 3.0 mm in average particle diameter. Out-of-sphericity thereof is preferably set no more than 0.5 times the particle diameter.

**[0023]** Size of the beryllium intermetallic compound phases included in the neutron multiplier material is preferably set no more than about 100  $\mu\text{m}$  in circle-equivalent diameter.

**[0024]** Furthermore, concentration of Fe included in the neutron multiplier material is preferably set no more than about 0.4 mass% and concentration of mixed oxides is preferably set no more than about 5.0 mass%.

**[0025]** Production methods of the neutron multiplier material according to the present invention will be described hereinafter.

**[0026]** The present invention does not require particular limits to the production method, however, a rotating electrode method and a powder metallurgy method, both of which are previously publicly known, are preferably applied.

- rotating electrode method

**[0027]** To employ the rotating electrode method to produce neutron multiplier material pebbles, first of all, preparing consumable electrode is necessary. To prepare the consumable electrode, providing metals, weights of which correspond to a ratio satisfying a weight ratio of the respective constituents of the desired intermetallic compound, melting the metals together, casting the mixture and machining the cast into a predetermined electrode shape are accomplished.

**[0028]** Next, preparing the neutron multiplier material pebbles from the obtained consumable electrode by means of

the rotating electrode method is accomplished.

**[0029]** Production conditions on this occasion are not particularly restricted, however, preferable conditions are described as follows.

- 5 - atmospheric gas pressure: 500 to 12000 Torr
- arc current: 100 to 1000 A
- rotation speed of the consumable electrode: 4 to 1000 m/s

10 - powder metallurgy method

**[0030]** To produce neutron multiplier material pebbles by means of this method, mixing intermetallic compound powder prepared to be a desired compositional ratio and metal powder having a weight so as to be a predetermined ratio of metal phase included in the neutron multiplier material, filling the mixed powder in spherical metal molds or such, forming green compacts in spherical shapes by means of cold pressing or such and sintered to be pebbles in a vacuum atmosphere are accomplished.

15 **[0031]** Fig. 1 shows a micro-metallograph of a neutron multiplier material obtained from the aforementioned rotating electrode method. The neutron multiplier material is an example which includes  $\text{Be}_{12}\text{Ti}$  (95 % in volumetric ratio) as a beryllium intermetallic compound phase and Be as a metallic phase.

20 **[0032]** As shown in the drawing, it is clearly understood that an  $\alpha$ -Be phase uniformly surrounds grains of  $\text{Be}_{12}\text{Ti}$  according to the present invention.

(example 1)

25 **[0033]** Neutron multiplier materials respectively including beryllium intermetallic compounds and metals, compositions of which are described in Table 1, are produced by means of the rotating electrode method or the powder metallurgy method. Particle sizes of the obtained neutron multiplier materials are 0.7 to 1.3 mm.

**[0034]** Results of evaluation about a neutron multiplying effect, an anti-swelling property, a ductility, a reactivity with the structural member, a reactivity with the vapor, a tritium inventory and a heat conductivity of each of thus obtained neutron multiplier materials are described in Table 2.

30 **[0035]** In addition, the respective properties are evaluated by the following procedures.

- neutron multiplying effect

35 **[0036]** A neutron multiplying effect is evaluated as a relative ratio to the neutron multiplying effect of the conventional metallic beryllium pebbles as 10, considering the neutron reaction cross section, the neutron absorption cross section and the neutron capture cross section of each of the constituent elements.

- anti-swelling property

40 **[0037]** An amount of swelling is measured in a condition that neutrons are irradiated to the test piece so as to generate 4000ppm of He therein at 700 degree C and the anti-swelling property is evaluated on a degree of swelling as three levels of SMALL (the swelling amount is not more than 0.5 vol%), MIDDLE (more than 0.5 vol% and not more than 3.0 vol%) and LARGE (more than 3.0 vol%), where the swelling amount is measured by volumetric change rate ( $\Delta V/V$  times 100 (%)).

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- ductility

**[0038]** A compression test is accomplished with a test piece of approximate 1 mm $\Phi$  pebble in diameter in a condition of compression speed:0.2mm/min and ductility is evaluated on shapes after the test.

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- reactivity with the structural members

55 **[0039]** A reactivity test with stainless steel in a He atmosphere of 6N for 800 to 1000 his accomplished and the reactivity is evaluated on a degree of reaction with the structural members as three levels of SMALL (reaction layer: no more than 50  $\mu\text{m}$ ), MIDDLE (reaction layer: more than 50  $\mu\text{m}$  and no more than 200  $\mu\text{m}$ ) and LARGE (reaction layer: more than 200  $\mu\text{m}$ ).

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- reactivity with the vapor

**[0040]** A reactivity test with the water vapor at 800 degree C is accomplished and the reactivity is evaluated on a degree of reaction with the water vapor as three levels of SMALL (rarely oxidized), MIDDLE (oxidized) and LARGE (destroyed by oxidation).

- tritium inventory

**[0041]** Tritium inventory is evaluated on an amount of tritium of the test piece accomplished of the swelling test, measured by the temperature-programmed desorption method. Specifically, the tritium inventory is evaluated on a degree of the tritium inventory as three levels of SMALL (extremely small amount), MIDDLE (some amount) and LARGE (large amount).

Table 1

No	Intermetallic compound	(vol%)	Metallic phase	(vol%)	Production method	Melting point (°C)
1	Be <sub>12</sub> Ti	100	-	-	rotating electrode	1550
2	↑	95	Be	5	↑	1530
3	↑	93	Be	7	↑	1500
4	↑	90	Be	10	powder metallurgy	1450
5	↑	85	Be	15	↑	1400
6	↑	55	Be	45	↑	1350
7	Be <sub>17</sub> Ti <sub>2</sub>	90	Be	10	↑	1550
8	Be <sub>12</sub> V	100	-	-	↑	1700
9	↑	95	Be	5	rotating electrode	1670
10	↑	93	Be	7	↑	1650
11	↑	90	Be	10	powder metallurgy	1600
12	↑	85	Be	15	↑	1550
13	Be <sub>13</sub> Zr	93	Be	7	rotating electrode	1720
14	↑	90	Be	10	powder metallurgy	1700
15	Be <sub>17</sub> Zr <sub>2</sub>	90	Be	10	↑	1500
16	Be <sub>12</sub> Nb	90	Be	10	↑	1600
17	Be <sub>17</sub> Nb <sub>2</sub>	90	Be	10	↑	1700
18	Be <sub>12</sub> Ta	93	Be	7	rotating electrode	1770
19	↑	90	Be	10	powder metallurgy	1750
20	Be <sub>17</sub> Ta <sub>2</sub>	90	Be	10	↑	1900
21	Be <sub>12</sub> Mo	95	Be	5	rotating electrode	1650
22	↑	90	Be	10	powder metallurgy	1600
23	Be <sub>12</sub> W	95	Be	5	rotating electrode	1700
24	↑	90	Be	10	powder metallurgy	1650
25	Be <sub>22</sub> W	90	Be	10	↑	1500
26	Be <sub>13</sub> Y	90	Be	10	↑	1800
27	Be <sub>12</sub> Ti	90	Zr	10	↑	1550
28	↑	90	Ti	10	↑	1550
29	↑	60	Ti	40	↑	1550

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(continued)

No	Intermetallic compound	(vol%)	Metallic phase	(vol%)	Production method	Melting point (°C)
30	↑	90	V	10	↑	1550
31	Be <sub>12</sub> V	90	Zr	10	↑	1550
32	↑	70	Zr	30	↑	1550
33	↑	90	Ti	10	↑	1550
34	↑	90	V	10	↑	1550
35	Be <sub>12</sub> Mo	90	Zr I	10	↑	1550
36	↑	90	Ti	10	↑	1550
37	↑	90	V	10	↑	1550
38	-	-	Be	100	rotating electrode	1280

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Table 2

No.	Neutron multiplying effect	Anti-swelling property	Ductility*	Reactivity with the structural members	Reactivity with the vapor	Tritium inventory	Thermal conductivity (W/m K)	remarks
1	0.90	SMALL	×	SMALL	SMALL	SMALL	40	comparative example
2	0.92	SMALL	○	SMALL	SMALL	SMALL	55	present invention
3	0.92	SMALL	○	SMALL	SMALL	SMALL	55	↑
4	0.93	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	65	↑
5	0.94	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	70	↑
6	0.95	MIDDLE	○	LARGE	LARGE	LARGE	90	↑
7	0.85	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	70	↑
8	0.92	SMALL	×	SMALL	SMALL	SMALL	40	comparative example
9	0.93	MIDDLE	○	MIDDLE	MIDDLE	MIDDLE	45	present invention
10	0.94	MIDDLE	○	MIDDLE	MIDDLE	MIDDLE	45	↑
11	0.94	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	55	↑
12	0.94	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	65	↑
13	0.85	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	70	↑
14	0.88	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	70	↑
15	0.80	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	70	↑
16	0.75	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	50	↑
17	0.70	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	65	↑
18	0.80	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	65	↑
19	0.82	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	65	↑
20	0.78	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	65	↑
21	0.85	SMALL	○	SMALL	SMALL	SMALL	50	↑
22	0.80	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	70	↑



(continued)

No.	Neutron multiplying effect	Anti-swelling property	Ductility*	Reactivity with the structural members	Reactivity with the vapor	Tritium inventory	Thermal conductivity (W/m K)	remarks
23	0.75	SMALL	○	SMALL	SMALL	SMALL	50	↑
24	0.70	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	70	↑
25	0.75	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	70	↑
26	0.90	MIDDLE	△	MIDDLE	MIDDLE	MIDDLE	70	↑
27	0.78	SMALL	△	SMALL	SMALL	SMALL	70	↑
28	0.88	SMALL	△	SMALL	SMALL	SMALL	70	↑
29	0.65	SMALL	○	MIDDLE	SMALL	SMALL	100	↑
30	0.88	SMALL	△	SMALL	SMALL	SMALL	70	↑
31	0.78	SMALL	△	SMALL	SMALL	SMALL	70	↑
32	0.50	SMALL	○	MIDDLE	SMALL	SMALL	90	↑
33	0.80	SMALL	△	SMALL	SMALL	SMALL	70	↑
34	0.80	SMALL	△	SMALL	SMALL	SMALL	70	↑
35	0.80	SMALL	△	SMALL	SMALL	SMALL	70	↑
36	0.80	SMALL	△	SMALL	SMALL	SMALL	70	↑
37	0.80	SMALL	△	SMALL	SMALL	SMALL	70	↑
38	1.00	LARGE	⊙	LARGE	LARGE	LARGE	170	conventional

**[0042]** As shown in Table 2, any of the examples of the present invention is excellent in the ductility and the anti-swelling property and has a proper neutron multiplying effect, a small tritium inventory and small reactivity with the structural members and the vapor.

**[0043]** In contrast to this, the comparative examples of No. 1 and No. 8 are poor in the ductility because they consist of 100 vol% of beryllium intermetallic compound.

**[0044]** The comparative example of No. 38 is excellent in the neutron multiplying effect and the ductility, because it consists of 100 vol% of metallic beryllium, but is large in the swelling and the tritium inventory and further large in the reactivity with the structural members and the vapor.

[SECOND EMBODIMENT]

**[0045]** Cases where the metallic phase is a matrix of the material has been described in the aforementioned first embodiment. The present invention can be embodied with any combinations of distinct beryllium intermetallic compounds.

**[0046]** Specifically, substances obtained from mixing and casting a combination of beryllium and titanium so that  $\text{Be}_{12}\text{Ti}$  and  $\text{Be}_{17}\text{Ti}_2$  coexist and are intermixed therein are ascertained to be remarkably improved in ductility as compared with simple substances of  $\text{Be}_{12}\text{Ti}$  and  $\text{Be}_{17}\text{Ti}_2$ .

**[0047]** A mixing ratio of  $\text{Be}_{12}\text{Ti}$  and  $\text{Be}_{17}\text{Ti}_2$  is not particularly limited, however, it is ascertained that the particularly preferable mixing ratios in a range of 10.5 to 2.0, or x in a range of 8.8 to 9.9 at% as described in a ratio x of Ti to Be, give especially excellent results.

**[0048]** Next, the present inventors conceived that any elements besides Ti might give similar effects and investigated various elements. As a result, it is ascertained that V, Mo, W, Zr, Nb and Ta give similar effects with Ti.

**[0049]** Furthermore, it is ascertained that the mixing ratios of the elements such that beryllium intermetallic compounds of  $\text{Be}_{12}\text{M}$  and  $\text{Be}_{17}\text{M}_2$  (where M is any one element selected from the group of V, Mo, W, Nb and Ta) (however, beryllium intermetallic compounds of  $\text{Be}_{13}\text{Zr}$  and  $\text{Be}_{17}\text{Zr}_2$  provided that M is Zr) coexist and are intermixed give excellent results as similar with Ti.

**[0050]** Moreover, concerning with metallographic structures of the composite phases of the beryllium intermetallic compounds, it is ascertained to be further advantageous in view of strength and ductility to set grain sizes of cast structures no more than 50  $\mu\text{m}$  and particularly preferably no more than 20  $\mu\text{m}$ .

**[0051]** Size of pebbles of the neutron multiplier material according to the present invention is preferably set about 0.1 through 3.0 mm in average particle diameter. Moreover, out-of-sphericity thereof is preferably set no more than 0.5 times the particle diameter.

**[0052]** Furthermore, concentration of Fe included in the neutron multiplier material is preferably set no more than about 0.4 mass% and concentration of mixed oxides is preferably set no more than about 5.0 mass%.

**[0053]** Next, production methods of the neutron multiplier material according to the present invention will be described hereinafter.

**[0054]** The present invention does not require particular limits to the production method, however, a rotating electrode method and a powder metallurgy method, both of which are previously publicly known, are preferably applied.

- rotating electrode method

**[0055]** To employ the rotating electrode method to produce neutron multiplier material pebbles, first of all, preparing consumable electrode is necessary. To prepare the consumable electrode, providing metals, weights of which correspond to a ratio satisfying a weight ratio of the respective constituents of the desired intermetallic compound, melting the metals together, casting the mixture and machining the cast into a predetermined electrode shape are accomplished.

**[0056]** Next, preparing the neutron multiplier material pebbles from the obtained consumable electrode by means of the rotating electrode method is accomplished.

**[0057]** Production conditions on this occasion are not particularly restricted, however, preferable conditions are described as follows.

- atmospheric gas pressure: 500 to 12000 Torr
- arc current: 100 to 1000 A
- rotation speed of the consumable electrode: 4 to 1000 m/s

- powder metallurgy method

**[0058]** To produce neutron multiplier material pebbles by means of this method, mixing intermetallic compound powder prepared to be a desired compositional ratio and metal powder having a weight so as to be a predetermined ratio of metal phase included in the neutron multiplier material, filling the mixed powder in spherical metal molds or such, forming

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green compacts in spherical shapes by means of cold pressing or such and sintered to be pebbles in a vacuum atmosphere are accomplished.

(example 2)

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**[0059]** Neutron multiplier materials respectively including beryllium intermetallic compounds and metals, compositions of which are described in Table 3, are produced by means of the rotating electrode method or the powder metallurgy method. Particle sizes of the obtained neutron multiplier materials are 0.7 to 1.3 mm.

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**[0060]** Results of evaluation about a neutron multiplying effect, an anti-swelling property, a ductility, a reactivity with the structural member, a reactivity with the vapor, a tritium inventory and a heat conductivity of each of thus obtained neutron multiplier materials are described in Table 4.

- ductility

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**[0061]** A compression test is accomplished with a test piece of approximate 1 mmΦ pebble in diameter in a condition of compression speed:0.2 mm/min and ductility is evaluated on a shape after the test.

- reactivity with the structural members

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**[0062]** A reactivity test with stainless steel in a He atmosphere of 6N for 800 to 1000 h is accomplished and the reactivity is evaluated on a degree of reaction with the structural members as three levels of SMALL (reaction layer: no more than 50 μm), MIDDLE (reaction layer: more than 50 μm and no more than 200 μm) and LARGE (reaction layer: more than 200 μm).

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- reactivity with the vapor

**[0063]** A reactivity test with the water vapor at 800 degree C is accomplished and the reactivity is evaluated on a degree of reaction with the water vapor as three levels of SMALL (rarely oxidized), MIDDLE (oxidized) and LARGE (destroyed by oxidation).

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- tritium inventory

**[0064]** Tritium inventory is evaluated on an amount of tritium of the test piece accomplished of the swelling test, measured by the temperature-programmed desorption method. Specifically, the tritium inventory is evaluated on degrees of the tritium inventory as three degrees of SMALL (extremely small amount), MIDDLE (some amount) and LARGE (large amount).

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Table 3

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No	Combination of intermetallic compounds	Composition ratio * (at%)	Production method	Crystal grain size (μm)
1	Be <sub>12</sub> Ti and Be <sub>17</sub> Ti <sub>2</sub>	8	rotational electrode	30
2	↑	8	HIP	20
3	↑	9	rotational electrode	10
4	↑	9	HIP	20
5	↑	10	rotational electrode	20
6	↑	10	HIP	30
7	Be <sub>12</sub> V and Be <sub>17</sub> V <sub>2</sub>	8	rotational electrode	35
8	↑	9	rotational electrode	25

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(continued)

No	Combination of intermetallic compounds	Composition ratio * (at%)	Production method	Crystal grain size (μm)
5 9	↑	9	HIP	35
10		10	rotational electrode	25
10 11	Be <sub>12</sub> Mo and Be <sub>17</sub> Mo <sub>2</sub>	8	rotational electrode	30
12	↑	9	rotational electrode	20
13	↑	9	HIP	25
15 14	↑	10	rotational electrode	25
15 15	Be <sub>12</sub> W and Be <sub>17</sub> W <sub>2</sub>	8	rotational electrode	35
20 16	↑	9	rotational electrode	25
17	↑	9	HIP	35
25 18	↑	10	rotational electrode	25
19	Be <sub>13</sub> Zr and Be <sub>17</sub> Zr <sub>2</sub>	8	rotational electrode	35
30 20	↑	9	rotational electrode	20
21	↑	9	HIP	25
22	↑	10	rotational electrode	40
35 23	Be <sub>12</sub> Nb and Be <sub>17</sub> Nb <sub>2</sub>	8	rotational electrode	30
24	t	9	rotational electrode	20
40 25	↑	9	HIP	25
26	↑	10	rotational electrode	25
45 27	Be <sub>12</sub> Ta and Be <sub>17</sub> Ta <sub>2</sub>	8	rotational electrode	35
28	↑	9	rotational electrode	25
29	↑	9	HIP	25
50 30	↑	10	rotational electrode	35
31	Simple substance of Be <sub>12</sub> Ti	7.7	rotational electrode	35
55 32	Be <sub>12</sub> Ti and Be	5	rotational electrode	50

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(continued)

No	Combination of intermetallic compounds	Composition ratio * (at%)	Production method	Crystal grain size ( $\mu\text{m}$ )
33	Simple substance of Be	-	rotational electrode	100

\*: x is a ratio of M to Be

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Table 4

No.	Neutron multiplying effect	Anti-swelling property	Ductility*	Reactivity with the structural members	Reactivity with the vapor	Tritium inventory	Thermal conductivity (W/m K)	remarks
1	0.89	SMALL	○	SMALL	SMALL	SMALL	40	present invention
2	0.89	↑	○	↑	↑	↑	40	↑
3	0.87	↑	⊙	↑	↑	↑	40	↑
4	0.87	↑	○	↑	↑	↑	40	↑
5	0.85	↑	○	↑	↑	↑	40	↑
6	0.85	↑	○	↑	↑	↑	40	↑
7	0.89	↑	○	↑	↑	↑	40	↑
8	0.87	↑	⊙	↑	↑	↑	40	↑
9	0.87	↑	○	↑	↑	↑	40	↑
10	0.85	↑	○	↑	↑	↑	40	↑
11	0.89	↑	○	↑	↑	↑	50	↑
12	0.87	↑	⊙	↑	↑	↑	50	↑
13	0.87	↑	○	↑	↑	↑	50	↑
14	0.85	↑	○	↑	↑	↑	50	↑
15	0.89	↑	○	↑	↑	↑	70	↑
16	0.87	↑	⊙	↑	↑	↑	70	↑
17	0.87	↑	○	↑	↑	↑	70	↑
18	0.85	↑	○	↑	↑	↑	70	↑
19	0.89	↑	○	↑	↑	↑	70	↑
20	0.87	↑	⊙	↑	↑	↑	70	↑
21	0.87	↑	○	↑	↑	↑	70	↑
22	0.85	↑	○	↑	↑	↑	70	↑
23	0.89	↑	○	↑	↑	↑	50	↑
24	0.87	↑	⊙	↑	↑	↑	50	↑

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(continued)

No.	Neutron multiplying effect	Anti-swelling property	Ductility*	Reactivity with the structural members	Reactivity with the vapor	Tritium inventory	Thermal conductivity (W/m K)	remarks
25	0.87	↑	○	↑	↑	↑	50	↑
26	0.85	↑	○	↑	↑	↑	50	↑
27	0.89	↑	○	↑	↑	↑	60	↑
28	0.87	↑	⊙	↑	↑	↑	60	↑
29	0.87	↑	○	↑	↑	↑	60	↑
30	0.85	↑	○	↑	↑	↑	60	↑
31	0.90	SMALL	×	SMALL	SMALL	SMALL	40	comparative example
32	0.92	↑	○	MIDDLE	MIDDLE	MIDDLE	55	↑
33	1.00	LARGE	⊙	LARGE	LARGE	LARGE	170	conventional

\*1) shapes after compression tests  
 ⊙:deformed (without fractures)    ○:deformed (with micro-fractures)  
 Δ:deformed (with small fractures)    ×:broken

**[0065]** As shown in Table 4, any of the examples of the present invention is excellent in the ductility and the anti-swelling property and has a high neutron multiplying effect, a small tritium inventory and small reactivity with the structural members and the vapor.

5 **[0066]** In contrast to this, the comparative example of No. 31 is poor in the ductility because this example consists of a simple substance of  $\text{Be}_{12}\text{Ti}$ .

**[0067]** The comparative example of No. 32 includes a metal phase as binder between beryllium intermetallic compound phases so that the ductility and the anti-swelling property are excellent, the tritium inventory is small and reactivity with the structural members and the vapor is small, however, the high neutron multiplying effect thereof is not satisfactory.

10 **[0068]** The comparative example of No. 33 is excellent in the neutron multiplying effect and the ductility, because it consists of 100 vol% of metallic beryllium, but is large in the swelling and the tritium inventory and further large in the reactivity with the structural members and the vapor.

[THIRD EMBODIMENT]

15 **[0069]** In a case where the present invention is embodied with a combination of the distinct beryllium intermetallic compounds, any of the materials according to the present invention has a particularly excellent property as a material facing to plasma.

20 **[0070]** Specifically, substances obtained from mixing and casting a combination of beryllium and titanium so that  $\text{Be}_{12}\text{M}$  and  $\text{Be}_{17}\text{M}_2$  coexist and are intermixed therein are ascertained to be remarkably improved in ductility as compared with simple substances of  $\text{Be}_{12}\text{M}$  and  $\text{Be}_{17}\text{M}_2$ .

**[0071]** A mixing ratio of  $\text{Be}_{12}\text{M}$  and  $\text{Be}_{17}\text{M}_2$  is not particularly limited, however, it is ascertained that the particularly preferable mixing ratios in a range of 10.5 to 2.0, or x in a range of 8.8 to 9.9 at% as described in a ratio x of M to Be, give especially excellent results.

25 **[0072]** Moreover, concerning with metallographic structures of the composite phases of the beryllium intermetallic compounds, it is ascertained to be further advantageous in view of strength to set grain sizes of cast structures no more than 30  $\mu\text{m}$  and particularly preferably no more than 20  $\mu\text{m}$ .

**[0073]** Next, production methods of the plasma facing material according to the present invention will be described hereinafter.

30 **[0074]** Beryllium powder or beryllium intermetallic compound powder is prepared so as to be a desired composition and the prepared powder is filled in a mold. Stainless steel is ordinarily applied to such a mold and accomplished with canning by means of electron-beam welding.

**[0075]** HIP is accomplished at 1200 to 1500 degree C and 100 to 200 MPa for approximate 1 to 5 hours by means of a HIP (hot isostatic pressing) machine.

35 **[0076]** Next, the material is taken out of the mold and finished with machining.

(Example 3)

**[0077]** The plasma facing materials respectively having compositions as shown in Table 5 are produced by means of the HIP method.

40 **[0078]** In this occasion, a particle size of the provided powder is 0.6  $\mu\text{m}$  and the HIP condition is that the temperature is 1300 degree C and the pressure is 150 MPa. Crystal particle sizes of the obtained plasma facing materials are in a range of 5 to 20  $\mu\text{m}$ .

**[0079]** Results of evaluation about a radiation loss, a sputtering property and a tritium absorbcency of each of thus obtained plasma facing materials are described in Table 6.

45 **[0080]** In addition, the respective properties are evaluated by the following procedures.

- radiation loss

50 **[0081]** Smaller atomic weight gets the radiation loss more preferable, hence average atomic weight of the compounds is employed for evaluation.

- sputtering property

55 **[0082]** A melting point is employed for evaluation of a physical sputtering property. Furthermore, a chemical sputtering property is on degrees of reactivity with hydrogen (at 600 degree C) as three levels of 0 (hardly react),  $\Delta$  (slightly react) and  $\times$  (considerably react).



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- tritium absorbcency

[0083] An amount of tritium absorbed in the material after being kept in a tritium atmosphere for 3 hours is measured by the temperature-programmed desorption method and the tritium absorbcency is evaluated on the measured value as three levels of LARGE, MIDDLE and SMALL.

Table 5

No	Element of M	Composition ratio * (at%)	Combination of intermetallic compounds	Crystal grain size (μm)
1	Ti	6.5	Be and Be <sub>12</sub> Ti	15
2	↑	9.0	Be <sub>12</sub> Ti and Be <sub>17</sub> Ti <sub>2</sub>	10
3	↑	10.0	↑	8
4	↑	12.0	Be <sub>17</sub> Ti <sub>2</sub> and Be <sub>3</sub> Ti	12
5	V	6.0	Be and Be <sub>12</sub> V	17
6	↑	9.0	Be <sub>12</sub> V and Be <sub>17</sub> V <sub>2</sub>	13
7	↑	10.0	↑	11
8	↑	12.0	Be <sub>17</sub> V <sub>2</sub> and Be <sub>3</sub> V	10
9	Mo	5.5	Be and Be <sub>12</sub> Mo	14
10	↑	9.0	Be <sub>12</sub> Mo and Be <sub>17</sub> Mo <sub>2</sub>	12
11	↑	10.0	↑	10
12	↑	12.0	Be <sub>17</sub> Mo <sub>2</sub> and Be <sub>3</sub> Mo	11
13	W	6.5	Be and Be <sub>12</sub> W	20
14	↑	9.0	Be <sub>12</sub> W and Be <sub>17</sub> W <sub>2</sub>	18
15	t	10.0	↑	16
16	↑	12.0	Be <sub>17</sub> W <sub>2</sub> and Be <sub>3</sub> W	5
17	Zr	7.0	Be and Be <sub>13</sub> Zr	18
18		9.0	Be <sub>13</sub> Zr and Be <sub>17</sub> Zr <sub>2</sub>	17
19		10.0	↑	15
20		12.0	Be <sub>17</sub> Zr <sub>2</sub> and Be <sub>3</sub> Zr	13
21	Nb	6.5	Be and Be <sub>12</sub> Nb	13
22		9.0	Be <sub>12</sub> Nb and Be <sub>17</sub> Nb <sub>2</sub>	12
23		10.0	↑	9
24		12.0	Be <sub>17</sub> Nb <sub>2</sub> and Be <sub>3</sub> Nb	10
25	Ta	6.0	Be and Be <sub>12</sub> Ta	12
26		9.0	Be <sub>12</sub> Ta and Be <sub>17</sub> Ta <sub>2</sub>	11
27		10.0	↑	9
28		12.0	Be <sub>17</sub> Ta <sub>2</sub> and Be <sub>3</sub> Ta	10
29	Ti	7.7	Simple substance of Be <sub>12</sub> Ti	15
30	none	0	Simple substance of Be	5

\*: x is a ratio of M to Be

Table 6

No	Radiation loss	Sputtering property		Tritium absorbent	remarks
		physical	chemical		
1	2.2	1500	○	SMALL	Present invention
2	2.5	1520	↑	↑	↑
3	2.6	1550	↑	↑	↑
4	2.8	1500	↑	↑	↑
5	3.6	1670	↑	↑	↑
6	3.9	1700	↑	↑	↑
7	4.1	1750	↑	↑	↑
8	4.3	1650	↑	↑	↑
9	2.9	1630	↑	↑	↑
10	3.1	1650	↑	↑	↑
11	3.2	1680	↑	↑	↑
12	3.4	1600	↑	↑	↑
13	4.2	1680	↑	↑	↑
14	4.4	1700	↑	↑	↑
15	4.5	1720	↑	↑	↑
16	4.7	1650	↑	↑	↑
17	2.7	1680	↑	↑	↑
18	2.8	1700	↑	↑	↑
19	2.9	1710	↑	↑	↑
20	3.1	1650	↑	↑	↑
21	2.9	1580	↑	↑	↑
22	3.0	1600	↑	↑	↑
23	3.1	1630	↑	↑	↑
24	3.3	1520	↑	↑	↑
25	4.0	1750	↑	↑	↑
26	4.2	1760	↑	↑	↑
27	4.3	1780	↑	↑	↑
28	4.4	1700	↑	↑	↑
29	2.3	1550	○	SMALL	Comparative example
30	1.9	1280	×	LARGE	↑

[0084] As shown in Table 6, any of the examples of the present invention has a small radiation loss, a small sputtering erosion and a small tritium absorbent.

[0085] In contrast to this, the comparative example of No. 29 is defective of brittleness at a room temperature though satisfactory in the other properties because this example consists of a simple substance of  $\text{Be}_{12}\text{Ti}$ .

[0086] Moreover, the comparative example of No. 30 is excellent in the radiation loss, because it consists of 100 % of metallic beryllium, but is poor in the sputtering property and the tritium absorbent.

[0087] Although the invention has been described above by reference to certain embodiments of the invention, the invention is not limited to the embodiments described above. Modifications and variations of the embodiments described above will occur to those skilled in the art, in light of the above teachings.

[0088] Moreover, throughout the present description and claims, the phrase "consisting essentially of --" is defined and used as a meaning of including -- as essential ingredients but excluding additional unspecified ingredients that would affect the basic and novel characteristics of the product. However, the phrase does not exclude a possibility that the product includes any other ingredients that would not affect the basic and novel characteristic of the product.

## INDUSTRIAL APPLICABILITY

[0089] The present invention provides neutron multiplier materials for nuclear fusion reactors, which are excellent in high-temperature properties and machinability so as to be high productivity, and further easy to handle. The present invention further provides plasma facing materials for nuclear fusion reactors, which lead to small sputtering erosion and small radiation loss in a case of being contaminated in the plasma and absorb a small amount of tritium.

## Claims

1. A material for a nuclear fusion reactor, the material consisting essentially of an alloy including at least one beryllium intermetallic compound phase and a base phase, **characterized in that** the base phase of the alloy consists of one or more metals selected from the group of Be, Zr, Ti and V.

2. The material for the nuclear fusion reactor of claim 1, wherein:

the beryllium intermetallic compound phase consists essentially of a compound of Be with one or more elements selected from the group of Ti, V, Zr, Nb, Ta, Mo, W and Y.

3. The material for the nuclear fusion reactor of claim 1, wherein:

a volumetric ratio of the beryllium intermetallic compound phase is 50 to 99 %.

4. The material for the nuclear fusion reactor of claim 1, wherein:

the alloy is produced by casting; and  
a crystal grain size of the alloy is no more than 50  $\mu\text{m}$ .

5. A material for a nuclear fusion reactor, the material is **characterized in** consisting essentially of:

two or more substances selected from the groups of  $\text{Be}_{12}\text{M}$  or  $\text{Be}_{13}\text{M}$ ,  $\text{Be}_{17}\text{M}_2$ , Be or M, wherein M is a metal element selected from the group of Ti, V, Mo, W, Zr, Nb and Ta, and a composition ratio x of M to Be is in a range of  $2.0 \leq x \leq 15.0$  (at-%).

6. The material for a nuclear fusion reactor according to claim 5, the material consisting essentially of:

$\text{Be}_{12}\text{M}$  or  $\text{Be}_{13}\text{M}$  and  $\text{Be}_{17}\text{M}_2$ ,  
wherein M is a metal element selected from the group of Ti, V, Mo, W, Zr, Nb and Ta, and a composition ratio x of M to Be is in a range of  $7.7 < x < 10.5$  (at-%).

7. The material for the nuclear fusion reactor of claim 5, wherein:

the alloy is produced by casting; and  
a crystal grain size of the alloy is no more than 50  $\mu\text{m}$ .

8. The material for the nuclear fusion reactor of claim 5, wherein:

the alloy is produced by powder metallurgy; and  
a crystal grain size of the alloy is no more than 50  $\mu\text{m}$ .

9. A neutron multiplier material for a nuclear fusion reactor comprising the material for the nuclear fusion reactor of claim 1.

10. A plasma facing material for a nuclear fusion reactor comprising the material for the nuclear fusion reactor of claim 5.

Patentansprüche

5

1. Material für einen Kernfusionsreaktor, wobei das Material im Wesentlichen aus einer Legierung besteht, die zumindest eine Beryllium-intermetallische Verbindung-Phase und eine Basis-Phase beinhaltet, **dadurch gekennzeichnet, dass** die Basis-Phase der Legierung aus einem oder mehr Metallen besteht, das/die aus der Gruppe von Be, Zr, Ti und V ausgewählt ist/sind.

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2. Material für den Kernfusionsreaktor nach Anspruch 1, wobei:

die Beryllium-intermetallische Verbindung-Phase im Wesentlichen aus einer Verbindung von Be mit einem oder mehr Elementen besteht, das/die aus der Gruppe von Ti, V, Zr, Nb, Ta, Mo, W und Y ausgewählt ist/sind.

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3. Material für den Kernfusionsreaktor nach Anspruch 1, wobei:

ein volumetrisches Verhältnis der Beryllium-intermetallischen Verbindung-Phase 50 bis 99% ist.

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4. Material für den Kernfusionsreaktor nach Anspruch 1, wobei:

die Legierung durch Gießen hergestellt ist; und eine Kristallkorngröße der Legierung nicht mehr als 50 µm ist.

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5. Material für einen Kernfusionsreaktor, wobei das Material **gekennzeichnet ist durch** im Wesentlichen bestehen aus:

zwei oder mehr Substanzen, die aus den Gruppen von Be<sub>12</sub>M oder Be<sub>13</sub>M, Be<sub>17</sub>M<sub>2</sub>, Be oder M ausgewählt sind, wobei M ein Metallelement ist, das aus der Gruppe von Ti, V, Mo, W, Zr, Nb und Ta ausgewählt ist, und ein Zusammensetzungsverhältnis x von M zu Be in einem Bereich von 2,0 ≤ x ≤ 15,0 (At.-%) ist.

30

6. Material für einen Kernfusionsreaktor nach Anspruch 5, wobei das Material im Wesentlichen besteht aus:

Be<sub>12</sub>M oder Be<sub>13</sub>M und Be<sub>17</sub>M<sub>2</sub>, wobei M ein Metallelement ist, das aus der Gruppe von Ti, V, Mo, W, Zr, Nb und Ta ausgewählt ist, und ein Zusammensetzungsverhältnis x von M zu Be in einem Bereich von 7,7 < x < 10,5 (At.-%) ist.

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7. Material für den Kernfusionsreaktor nach Anspruch 5, wobei:

die Legierung durch Gießen hergestellt ist; und eine Kristallkorngröße der Legierung nicht mehr als 50 µm ist.

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8. Material für den Kernfusionsreaktor nach Anspruch 5, wobei:

die Legierung durch Pulvermetallurgie hergestellt ist; und eine Kristallkorngröße der Legierung nicht mehr als 50 µm ist.

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9. Neutronenvervielfachungsmaterial für einen Kernfusionsreaktor, das das Material für den Kernfusionsreaktor nach Anspruch 1 umfasst.

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10. Plasma-zugewandtes Material für einen Kernfusionsreaktor, dass das Material für den Kernfusionsreaktor nach Anspruch 5 umfasst.

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Revendications

1. Matériau pour un réacteur de fusion nucléaire, le matériau consistant essentiellement en un alliage incluant au moins une phase de composé intermétallique de béryllium et une phase de base, **caractérisé en ce que**

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la phase de base de l'alliage consiste en un ou plusieurs métal/métaux choisi(s) parmi le groupe de Be, Zr, Ti et V.

2. Matériau pour le réacteur de fusion nucléaire selon la revendication 1, dans lequel :

5 la phase de composé intermétallique de béryllium consiste essentiellement en un composé de Be avec un ou plusieurs élément(s) choisi(s) parmi le groupe de Ti, V, Zr, Nb, Ta, Mo, W et Y.

3. Matériau pour le réacteur de fusion nucléaire selon la revendication 1, dans lequel :

10 un rapport volumétrique de la phase de composé intermétallique de béryllium est 50 à 99%.

4. Matériau pour le réacteur de fusion nucléaire selon la revendication 1, dans lequel :

15 l'alliage est produit par coulage ; et  
une taille de grains cristallins de l'alliage n'est pas supérieure à 50  $\mu\text{m}$ .

5. Matériau pour un réacteur de fusion nucléaire, le matériau est **caractérisé en ce que** consistant essentiellement en :

20 deux substances ou plus choisies parmi les groupes de  $\text{Be}_{12}\text{M}$  ou  $\text{Be}_{13}\text{M}$ ,  $\text{Be}_{17}\text{M}_2$ , Be ou M, dans lesquelles M est un élément métal choisi parmi le groupe de Ti, V, Mo, W, Zr, Nb et Ta, et un rapport de composition x de M sur Be est dans une plage de  $2,0 \leq x \leq 15,0$  (% à l'atmosphérique).

6. Matériau pour un réacteur de fusion nucléaire selon la revendication 5, le matériau consistant essentiellement en :

25  $\text{Be}_{12}\text{M}$  ou  $\text{Be}_{13}\text{M}$  et  $\text{Be}_{17}\text{M}_2$ , dans lesquelles M est un élément métal choisi parmi le groupe de Ti, V, Mo, W, Zr, Nb et Ta, et un rapport de composition x de M sur Be est dans une plage de  $7,7 < x < 10,5$  (% à l'atmosphérique).

7. Matériau pour le réacteur de fusion nucléaire selon la revendication 5, dans lequel :

30 l'alliage est produit par coulage ; et  
une taille de grains cristallins de l'alliage n'est pas supérieure à 50  $\mu\text{m}$ .

8. Matériau pour le réacteur de fusion nucléaire selon la revendication 5, dans lequel :

35 l'alliage est produit par métallurgie des poudres ; et  
une taille de grains cristallins de l'alliage n'est pas supérieure à 50  $\mu\text{m}$ .

9. Matériau de multiplicateur à neutrons pour un réacteur de fusion nucléaire comprenant le matériau pour le réacteur de fusion nucléaire selon la revendication 1.

10. Matériau face au plasma pour un réacteur de fusion nucléaire comprenant le matériau pour le réacteur de fusion nucléaire selon la revendication 5.

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FIG.1

