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(54) TERNARY TITANIUM ALLOY, A METHOD FOR PRODUCING THEREOF AND USE OF THE SAME

TERNÄRE TITANLEGIERUNG, VERFAHREN ZU IHRER HERSTELLUNG UND VERWENDUNG

ALLIAGE TERNAIRE DE TITANE, SON PROCÉDÉ DE PRODUCTION ET SON UTILISATION

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(73) Proprietor: **KGHM Polska Miedz Spólka Akcyjna**
59-301 Lubin (PL)

(72) Inventors:
- **KWASNIAK, Piotr**
  01-134 Warszawa (PL)
- **MUZYK, Marek**
  00-714 Warszawa (PL)

(74) Representative: **AOMB Polska Sp. z.o.o.**
ul. Rondo Ignacego Daszynskiego 1
00-843 Warsaw (PL)

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Description

[0001] The invention relates to a ternary alloy of titanium, silicon, and rhenium, and a method for producing a ternary alloy of titanium, silicon, and rhenium, which allows for providing high strength or plasticity, and to its applications.

[0002] Currently produced titanium alloys are classified according to their phase structure (a phase -a uniform part of a metal or an alloy with a specific and periodic atomic structure), which shapes the mechanical and physicochemical properties of a material; they include [1-3]:

- single-phase alpha alloys - having a hexagonal structure (phase),
- single-phase beta alloys - having a regular, spatially centred structure,
- two-phase alpha+beta alloys - being a mixture of the above phases,
- metastable alloys - materials having a metastable reference framework, which can undergo changes under working conditions due to external factors, e.g. stress and temperature
- ordered alloys - materials with the predominant share of ordered phases (the alloying elements occupy specific positions in the crystal structure), e.g. TiNi.

[0003] Optimisation of the required characteristics of the individual systems has led to further development of the chemical composition and the construction of new materials. The main examples of modern Ti alloys include pseudo-alpha alloys, which are basically two-phase alloys, but the share of the alpha phase is predominant - the remaining elements of the structure usually account for several percent by volume [1-3]. Pseudo-alpha alloys have been designed to work at high temperatures, and they are characterised by a complex chemical composition, e.g. a Ti-6-2-4-2-S alloy with the following composition: Ti-6Al-2Sn-4Zr-2Mo-0.1Si, TIMETAL 1100: Ti-6Al-2.7Sn-4Zr-0.4Mo-0.4Si, TIMTETAL 685: Ti-6Al-5Zr-0.5Mo-0.25Si, TIMETAL 834 Ti-5.8Al-4Sn-3.5Zr-0.5Mo-0.7Nb-0.35Si-0.06C [2,5]. Alloying elements with the highest share are Al, Sn, and Zr, serving the function of stabilisers of the alpha phase, while the remaining elements are responsible for the precipitation of additional phases - the beta phase and intermetallic precipitates. Moreover, a special function is served by the silicon additive, which hardens the material very strongly, reduces volume diffusion, considerably inhibits the creep of the material at high temperatures, and reduces oxidation [1-3,5]. The main drawback of pseudo-alpha alloys is their very complex chemical composition, hindering their further improvement, and low ductility, usually not exceeding 12% of the breaking strain, due to which these alloys cannot be freely shaped at low temperatures.

[0004] The document FR2213986B1 presents a titanium alloy with the following additives: 0.05-0.1% Re, 6-7.5% Al, 0.2-2% Zr, 0.5-2% Sn, 1.5-2.7% Mo, 0.2-1.2% W, 0.1-0.35% Si, and 0.2-0.5% Cr. This alloy is characterised by high strength and thermal stability at a temperature of 500°C, a high fatigue limit and resistance to creep. If is found useful, e.g. in the blades of gas and steam turbines. This alloy has a very complex chemical composition - it contains numerous alloying additives.

[0005] Similarly, the document EP2687615B1 describes a titanium alloy with good resistance to oxidation, characterised by high strength at elevated temperatures. The alloy can contain between 4.5 and 7.5% of Al, between 2 and 8% of TiN, between 1.5 and 6.5% of Nb, between 0.1 and 2.5% of Mo, between 0.1 and 0.6% of Si, up to 0.2% of O, and up to 0.10% of C. This alloy does not contain rhenium; moreover, the alloy contains numerous alloying additives.

[0006] The document US10183331B2 discloses a method for producing a titanium alloy using the SPS method, meaning spark plasma sintering from titanium powders. The alloy contains 42% to 49% of aluminium, between 0.05% and 1.5% of boron, at least 0.2% of at least one element selected from a group consisting of tungsten, rhenium, and zirconium, possibly 0% to 5% of at least one element selected from a group consisting of chromium, niobium, molybdenum, silicon, and carbon, with the remaining part being titanium.

[0007] The document CN106119603A presents an alloy resistant to corrosion, containing the following elements: 6-7 parts by weight of copper, 6-7 parts by weight of tantalum, 5-6 parts by weight of chromium, 6-7 parts by weight of tungsten, 1.5-2 parts by mass of rhenium, 0-1.5 parts by weight of silicon, 7-8 parts by mass of cobalt, and 26-38 parts by mass of titanium.

[0008] The document US20040094241A1 presents an oxidation resistant, high strength titanium alloy, particularly adapted for use in the manufacture of automotive exhaust system components and other applications requiring oxidation resistance and strength at elevated temperatures. The alloy comprises, in weight percent, iron less than 0.5, or 0.2 to less than 0.5% oxygen 0.02 to less than 0.15%, silicon 0.15 to 0.6%, and balance titanium. Optional alloying elements are Al, Nb, V, Mo, Sn, Zr, Ni, Cr and Ta, with a total content of less than 1.5.

[0009] The ternary titanium alloy according to the invention consists of between 0.4 and 0.6% by weight of silicon, between 0.2 and 1% by weight of rhenium, impurities in the form of oxygen, nitrogen, carbon, and iron, in a total amount below 1.05 wt% and titanium up to 100% by weight with respect to the weight of the alloy.

[0010] Preferably, the silicon content is 0.45 wt%.

[0011] Most preferably, the rhenium content is between 0.5 and 1 wt%, preferably 1 wt%.

[0012] The method for producing a ternary titanium alloy according to the invention comprises the following steps:

(i) preparing a mixture containing titanium, silicon,

and rhenium, the mixture containing titanium, 0.4-0.6% by weight of silicon, between 0.2 and 1% by weight of rhenium, and possible impurities in the form of oxygen, nitrogen, carbon, and iron, preferably in a total amount below 1.05 wt %;
(ii) recasting the mixture at least once at a temperature at least equal to the melting point of Re;
(iii) casting the alloy;
(iv) performing homogenisation annealing at a temperature at least equal to the $\alpha \rightarrow \beta$ transition temperature of the alloy;
(v) cooling the alloy in water from the β phase to the α phase;
(vi) performing alloy forming processes;
(vii) performing recrystallisation annealing;
(viii)cooling the resulting material.

[0013] Preferably, in step (ii), the recasting temperature is higher than the melting point of Re and lower than the boiling point of Ti.

[0014] Recasting of the mixture in step (ii) can be performed using the arc melting method.

[0015] Preferably, recasting of the mixture in step (ii) is performed five times.

[0016] Preferably, homogenisation annealing in step (iv) is performed at a temperature of at least 882°C, preferably at least 900°C.

[0017] Optionally, homogenisation annealing in step (iv) is performed for a time of at least 30 minutes.

[0018] Most preferably, cooling in step (v) is performed in water, preferably at room temperature.

[0019] In step (vi), forming processes can be performed by cold rolling of the cooled alloy.

[0020] Preferably, cold rolling in step (vi) is performed until reaching a reduction of at least 50% of the thickness of the material, preferably 50-80% of the thickness of the material.

[0021] Preferably, recrystallisation annealing in step (vii) is performed at a temperature between 810 and 830°C, preferably 820°C, and cooling is performed in accordance with step (viii) with a furnace, preferably at a rate of at least 1°C/min, or in the air, preferably at room temperature.

[0022] Alternatively, recrystallisation annealing in step (vii) is performed at a temperature higher than 882°C, preferably approximately 950°C, and cooling is performed in accordance with step (viii) in water.

[0023] Preferably, recrystallisation annealing in step (vii) is performed for a time of at least 10 minutes, preferably for a time of 10 minutes.

[0024] In step (vi), forming processes can be performed by hot forging above the α -> β transition temperature.

[0025] The ternary alloys according to the invention are applicable to the production of bearing elements of lightweight constructions and/or critical elements operating at high temperatures, preferably valves, connecting rods, shafts and/or structural elements, preferably bodies, exhaust gas discharge collectors and/or engine sheathing elements and/or drives and/or blades and/or controls of gas turbines.

[0026] It should be pointed out that the $\alpha \rightarrow \beta$ transition temperature of the alloy is 882°C, the melting point of rhenium is 3185°C, and the boiling point of titanium is approximately 3287°C.

[0027] The object of the invention is presented in an embodiment in the drawing, in which Fig. 1 presents the microstructure of a Ti-Si-1Re alloy in a state of equilibrium, i.e. after slow cooling from 820°C (treatment A) with visible intercrystalline precipitates - type I, and located inside the grains - type II (transmission electron microscopy); Fig. 2 presents the microstructure of a Ti-Si-Re alloy after fast cooling from 950°C (treatment B) with indicated martensite plates and precipitates of Ti-Si phases (transmission electron microscopy and electron diffraction); Fig. 3 presents the mechanical properties of pure titanium, Ti-Re and Ti-Si alloys (the commercial Timetal XT alloy indicated as TiXT), and Ti-Si-Re alloys, materials in a normalised condition after type A heat treatment, i.e. slow cooling from 820°C (the static tension test), Fig. 4 presents the structure (a) and mechanical properties (b) of pure titanium, Ti-Re and Ti-Si alloys (the commercial Timetal XT alloy indicated as TiXT), and Ti-Si-Re alloys - materials in a metastable condition after supersaturation from a temperature of 950°C, i.e. after treatment B (EBSD images of the microstructures of selected systems, and the static tension test).

Embodiment:

[0028] Ternary Ti-Si-Re alloys were prepared using the commercial Timetal XT alloy, containing 0.45 wt% of silicon. This material was recast with a rhenium additive, using the following procedure:

(i) Preparing a mixture of the commercial Timetal XT alloy with the rhenium additive, the mixture containing 0.5% and 1% by weight of rhenium, the rest being titanium and possible impurities, the maximum total concentration of O, N, C, and Fe impurities not exceeding 1.05% by weight.
(ii) Recasting the input materials five times using the arc melting method. The maximum temperature of the process did not exceed the boiling point of Ti, and at the same time it was lower than the melting point of Re.

[0029] Repeated recasting is used when mixing metals with a considerable difference in the melting point, and it favours uniform distribution of the alloying elements. The work was performed using a BOHLER Arc Melting System AM 500 machine, under high vacuum conditions (10^{-3} - 10^{-5} mbar), and recasting was performed at a temperature not exceeding the boiling point of Ti, and at the same time higher than the melting point of Re.

[0030] It was possible to use a lower number of recast-

ings (at least one recasting), but the minimum number of substrate recasting cycles should enable producing a chemically homogeneous alloy.

(iii) Casting the alloy
(iv) Homogenisation annealing

[0031] Homogenisation annealing was performed at a temperature above the α->β transition temperature of the alloy, i.e. above 882°C. In an embodiment, annealing was performed at a temperature of 900°C and over a time of 30 minutes. This step was supposed to homogenise the microstructure (elimination of unpreferable morphology comprising zones of frozen grains, columnar grains, and dendrites of variable size) and chemical composition.

(v) Cooling in water

[0032] Cooling in water from the temperature of a single-phase solution, from the β phase to the α phase, prevented the creation of precipitates which could hinder further treatment. Because of the use of water, the material was cooled down in several seconds, due to which there was no time for the action of diffusion - this prevented the process of creating precipitates and/or nucleation of new phases (to generate them, it is necessary to perform cooling 'with a furnace' for at least several minutes, or slow cooling in the air).

(vi) Cold rolling

[0033] Cold rolling of the cooled alloy was performed until reaching a 50-80% reduction in the thickness of the material. The forming processes enabled the introduction of a considerable number of structural defects constituting recrystallisation nuclei, which were necessary to perform the next step.

(vii) Recrystallisation annealing and (vii) cooling

[0034] The final step of heat treatment was performed in two versions: A and B

Treatment A: Recrystallisation annealing at a temperature of 820°C, minimum time of 10 minutes, cooling in the air or with a furnace. This step of the treatment was performed at a temperature close to the end of stability of the α-Ti phase, resulting in full recrystallisation of the material and obtaining a homogeneous, equiaxial microstructure (the reference condition for commercial materials).
Treatment B: Recrystallisation annealing at a temperature of 950°C, minimum time of 10 minutes, cooling in water. This version of treatment was performed at the temperature of stability of the β phase. Fast cooling in water resulted in a metastable α-Ti structure, supersaturated with rhenium, with a minimal amount of precipitates.

[0035] For comparative purposes, binary Ti-Re alloys were also prepared. The input materials: Ti with purity of 99.98 wt% and Re with purity of 99.9 wt% (according to the received technical specification) were cut and cleaned chemically and ultrasonically. Four compositions/mixtures of substrates were prepared, with the following Re concentrations: 0 (pure Ti), 0.2 wt%, 0.5 wt%, and 1 wt%, which constituted an input for the production of solid materials. The binary alloys were prepared using the same method as for the ternary alloys, but using only treatment A in step (vii).

Results:

[0036] Heat treatment A resulted in achieving a homogeneous, equiaxial structure of the material, consisting of a hexagonal phase saturated with rhenium and silicon, and two types of precipitates of a submicrometric size, present inside the grains and on their boundaries, as presented in Figure 1. Heat treatment B resulted in shaping a dispersed martensitic structure (a supersaturated hexagonal solution of Ti), with thickness of martensite plates in the order of 200 nm, with larger alpha grains and TiSi precipitates - Figs. 2 and 4.

[0037] The different morphology of the Ti-Si-Re alloy achieved by means of two heat treatments resulted in significantly different properties of the material, which are presented in Figures 3 and 4. Type A treatment allowed for achieving high strength and very high plasticity - the yield point higher by approximately 100 MPa, and the breaking strain higher by 11% compared to the commercial Timetal XT alloy with a composition of Ti-0.5Si (0.5 wt% ofSi). In a relative aspect, the increase in the yield point and the breaking strain was 20% and 40%, respectively. Compared to pure Ti, the yield point increased by 225%, and the Ti-Si-Re alloy retained over 80% of plasticity of pure Ti, which was unheard-of in the previous solutions.

[0038] The use of the B-type treatment increased the strength of the Ti-Si-Re alloy to a level of 950 MPa - the tensile strength, decreasing the plasticity of the alloy to a level of 17% of the breaking strain. In the context of commercial solutions, increases in strength of 40% and 147% were achieved for the Timetal XT alloy (Ti-05Si) and pure titanium, respectively.

[0039] Main advantageous effects achieved as a result of using the invention:

- A simplified chemical composition of the alloy compared to common commercial solutions, facilitating control of the material structure.
- A low total share of alloying elements amounting to 1.5 wt%.
- The ability to control the mechanical properties of the material in a wide range, depending on the used treatment - very good plasticity and high strength (treatment A) or very high strength, retaining 17% of the breaking strain (treatment B), which exceeds the

capacities of other pseudo-alpha alloys.

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[0040]

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Claims

1. A ternary titanium alloy, consisting of between 0.4 and 0.6% by weight of silicon, between 0.2 and 1% by weight of rhenium, impurities in the form of oxygen, nitrogen, carbon, and iron, in a total amount below 1.05 wt% and titanium up to 100% by weight with respect to the weight of the alloy.

2. The alloy according to claim 1, **characterised in that** its silicon content is 0.45 wt%.

3. The alloy according to claim 1 or 2, **characterised in that** its rhenium content is between 0.5 and 1 wt%, preferably 1 wt%.

4. A method for producing a ternary titanium alloy, comprising the following steps:

   (i) preparing a mixture containing titanium, silicon, and rhenium, the mixture containing titanium, 0.4-0.6% by weight of silicon, between 0.2 and 1% by weight of rhenium, and possible impurities in the form of oxygen, nitrogen, carbon, and iron, preferably in a total amount below 1.05 wt%;
   (ii) recasting the mixture at least once at a temperature at least equal to the melting point of Re;
   (iii) casting the alloy;
   (iv) performing homogenisation annealing at a temperature at least equal to the $\alpha \rightarrow \beta$ transition temperature of the alloy;
   (v) cooling the alloy in water from the β phase to the α phase;
   (vi) performing alloy forming processes;
   (vii) performing recrystallisation annealing;
   (viii) cooling the resulting material.

5. The method according to claim 4, **characterised in that** in step (ii), the recasting temperature is higher than the melting point of Re and lower than the boiling point of Ti.

6. The method according to claim 4 or 5, **characterised in that** recasting of the mixture in step (ii) is performed using the arc melting method.

7. The method according to claim 6, **characterised in that** recasting of the mixture in step (ii) is performed five times.

8. The method according to any of the claims from 4 to 7, **characterised in that** homogenisation annealing in step (iv) is performed at a temperature of at least 882°C, preferably at least 900°C.

9. The method according to any of the claims from 4 to 8, **characterised in that** homogenisation annealing in step (iv) is performed for a time of at least 30 minutes.

10. The method according to any of the claims from 4 to 9, **characterised in that** cooling in step (v) is performed in water, preferably at room temperature.

11. The method according to any of the claims from 4 to 10, **characterised in that** in step (vi), the forming processes are performed by cold rolling of the cooled alloy.

12. The method according to claim 11, **characterised in that** cold rolling in step (vi) is performed until reaching a reduction of at least 50% of the thickness of the material, preferably 50-80% of the thickness of the material.

13. The method according to claim 11 or 12, **characterised in that** recrystallisation annealing in step (vii) is performed at a temperature between 810 and 830°C, preferably 820°C, and cooling is performed in accordance with step (viii) with a furnace, preferably at a rate of at least 1°C/min, or in the air, preferably at room temperature.

14. The method according to claim 11 or 12, **characterised in that** recrystallisation annealing in step (vii) is performed at a temperature higher than 882°C, preferably approximately 950°C, and cooling is performed in accordance with step (viii) in water.

15. The method according to claim 13 or 14, **characterised in that** recrystallisation annealing in step (vii)

is performed for a time of at least 10 minutes, preferably for a time of 10 minutes.

16. The method according to any of the claims from 4 to 10, **characterised in that** in step (vi), the forming processes are performed by hot forging above the α -> β transition temperature.

17. Use of the ternary alloys according to any of the claims from 1 to 3 for the production of bearing elements of lightweight constructions and/or critical elements operating at high temperatures, preferably valves, connecting rods, shafts and/or structural elements, preferably bodies, exhaust gas discharge collectors and/or engine sheathing elements and/or drives and/or blades and/or controls of gas turbines.

Patentansprüche

1. Ternäre Titanlegierung, **dadurch gekennzeichnet, dass** sie aus Silizium in einer Menge von 0,4 bis 0,6 Gew.-%, Rhenium in einer Menge von 0,2 bis 1 Gew.-%, Verunreinigungen in Form von Sauerstoff, Stickstoff, Kohlenstoff und Eisen, vorzugsweise in einer Gesamtmenge von weniger als 1,05 Gew.-%, und Titan bis zu 100 Gew.-%, bezogen auf das Gewicht der Legierung, besteht.

2. Die Legierung nach Anspruch 1, **dadurch gekennzeichnet, dass** ihr Siliziumgehalt 0,45 Gew.-% beträgt.

3. Die Legierung nach Anspruch 1 oder 2, **dadurch gekennzeichnet, dass** ihr Rheniumgehalt im Bereich von 0,5 bis 1 Gew.-%, vorzugsweise 1 Gew.-%, liegt.

4. Das Verfahren zur Herstellung einer ternären Titanlegierung, **dadurch gekennzeichnet, dass** es die folgenden Schritte umfasst:

(i) die Herstellen einer Mischung, die Titan, Silizium und Rhenium enthält, wobei die Mischung Titan, Silizium in einer Menge von 0,4 bis 0,6 Gew.-%, Rhenium in einer Menge von 0,2 bis 1 Gew.-% und mögliche Verunreinigungen in Form von Sauerstoff, Stickstoff, Kohlenstoff und Eisen enthält, vorzugsweise in einer Gesamtmenge von weniger als 1,05 Gew.-%,
(ii) mindestens einmaliges Umgießen der Mischung bei einer Temperatur, die mindestens dem Schmelzpunkt von Re entspricht;
(iii) das Gießen der Legierung,
(iv) die Durchführung eines Homogenisierungsglühens bei einer Temperatur, die mindestens der $\alpha \rightarrow \beta$-Übergangstemperatur der Legierung entspricht;
(v) die Abkühlen der Legierung in Wasser von der β-Phase zur α-Phase;
(vi) die Durchführung von Legierungsformungsprozessen;
(vii) die Durchführung eines Rekristallisationsglühens;
(viii) die Abkühlung des erhaltenen Materials.

5. Das Verfahren nach Anspruch 4, **dadurch gekennzeichnet, dass** in Schritt (ii) die Temperatur beim Umgießen höher als der Schmelzpunkt von Re und niedriger als der Siedepunkt von Ti ist.

6. Das Verfahren nach Anspruch 4 oder 5, **dadurch gekennzeichnet, dass** das Umgießen der Mischung in Schritt (ii) unter Verwendung des Lichtbogen-Schmelzverfahrens durchgeführt wird.

7. Das Verfahren nach Anspruch 6, **dadurch gekennzeichnet, dass** das Umgießen der Mischung in Schritt (ii) fünfmal durchgeführt wird.

8. Das Verfahren nach einem der Ansprüche 4 bis 7, **dadurch gekennzeichnet, dass** das Homogenisierungsglühen in Schritt (iv) bei einer Temperatur von mindestens 882° C, vorzugsweise mindestens 900° C, durchgeführt wird.

9. Das Verfahren nach einem der Ansprüche 4 bis 8, **dadurch gekennzeichnet, dass** das Homogenisierungsglühen in Schritt (iv) für eine Zeit von mindestens 30 Minuten durchgeführt wird.

10. Das Verfahren nach einem der Ansprüche 4 bis 9, **dadurch gekennzeichnet, dass** die Kühlung in Schritt (v) in Wasser, vorzugsweise bei Raumtemperatur, durchgeführt wird.

11. Das Verfahren nach einem der Ansprüche 4 bis 10, **dadurch gekennzeichnet, dass** in Schritt (vi) die Umformprozesse durch das Kaltwalzen der abgekühlten Legierung durchgeführt werden.

12. Das Verfahren nach Anspruch 11, **dadurch gekennzeichnet, dass** das Kaltwalzen in Schritt (vi) so lange durchgeführt wird, bis eine Verringerung von mindestens 50 % der Dicke des Materials, vorzugsweise 50-80 % der Dicke des Materials, erreicht wird.

13. Das Verfahren nach Anspruch 11 oder 12, **dadurch gekennzeichnet, dass** das Rekristallisationsglühen in Schritt (vii) bei einer Temperatur zwischen 810 und 830° C, vorzugsweise 820° C, durchgeführt wird und die Abkühlung gemäß Schritt (viii) in einem Ofen, vorzugsweise mit einer Rate von mindestens 1° C/min, oder an der Luft, vorzugsweise bei Raumtemperatur, erfolgt.

14. Das Verfahren nach Anspruch 11 oder 12, **dadurch gekennzeichnet, dass** das Rekristallisationsglühen in Schritt (vii) bei einer Temperatur von mehr als 882° C, vorzugsweise etwa 950° C, durchgeführt wird und die Abkühlung nach Schritt (viii) in Wasser erfolgt.

15. Das Verfahren nach Anspruch 13 oder 14, **dadurch gekennzeichnet, dass** das Rekristallisationsglühen in Schritt (vii) für eine Zeit von mindestens 10 Minuten, vorzugsweise für eine Zeit von 10 Minuten, durchgeführt wird.

16. Das Verfahren nach einem der Ansprüche 4 bis 10, **dadurch gekennzeichnet, dass** in Schritt (vi) die Umformprozesse durch das Warmschmieden oberhalb der Übergangstemperatur von α -> β durchgeführt werden..

17. Die Verwendung der ternären Legierungen nach einem der Ansprüche 1 bis 3 zur Herstellung von Lagerelementen in Leichtbauweise und/oder kritischen, bei hohen Temperaturen betriebenen Elementen, vorzugsweise Ventilen, Pleuelstangen, Wellen und/oder Strukturelementen, vorzugsweise Körpern, Abgassammlern und/oder Motorverkleidungselementen und/oder Antrieben und/oder Schaufeln und/oder Steuerungen von Gasturbinen.

Revendications

1. Un alliage ternaire de titane, **caractérisé en ce qu'**il est composé de 0,4 à 0,6 % en poids de silicium, de 0,2 à 1 % en poids de rhénium, d'impuretés sous forme d'oxygène, d'azote, de carbone et de fer, de préférence en quantité totale inférieure à 1,05 % en poids, et de titane jusqu'à 100 % en poids par rapport au poids de l'alliage.

2. L'alliage selon la revendication 1, **caractérisé en ce que** sa teneur en silicium est de 0,45 % en poids.

3. L'alliage selon la revendication 1 ou 2, **caractérisé en ce que** sa teneur en rhénium est de 0,5 à 1 % en poids, de préférence 1 % en poids.

4. Un procédé de production d'un alliage ternaire de titane, **caractérisé en ce qu'**il comprend les étapes suivantes :

   (i) préparation d'un mélange contenant du titane, du silicium et du rhénium, le mélange contenant du titane, 0,4-0,6 % en poids de silicium, de 0,2 à 1 % en poids de rhénium et d'éventuelles impuretés sous forme d'oxygène, d'azote, de carbone et de fer, de préférence dans une quantité totale inférieure à 1,05 % en poids ;
   (ii) refonte du mélange au moins une fois à une température au moins égale au point de fusion de Re ;
   (iii) coulée de l'alliage ;
   (iv) réalisation d'un recuit d'homogénéisation à une température au moins égale à la température de transition $\alpha \rightarrow \beta$ de l'alliage ;
   (v) refroidissement de l'alliage dans l'eau, de la phase β à la phase α ;
   (vi) réalisation de processus de formage d'alliages ;
   (vii) réalisation d'un recuit de recristallisation ;
   (viii) refroidissement du matériau obtenu.

5. Le procédé selon la revendication 4, **caractérisé en ce qu'**à l'étape (ii), la température de refonte est supérieure au point de fusion de Re et inférieure au point d'ébullition de Ti.

6. Le procédé selon la revendication 4 ou 5, **caractérisé en ce que** la refonte du mélange à l'étape (ii) est effectuée en utilisant le procédé de fusion à l'arc.

7. Le procédé selon la revendication 6, **caractérisé en ce que** la refonte du mélange à l'étape (ii) est effectuée cinq fois.

8. Le procédé selon l'une des revendications 4 à 7, **caractérisé en ce que** le recuit d'homogénéisation à l'étape (iv) est effectué à une température d'au moins 882°C, de préférence d'au moins 900°C.

9. Le procédé selon l'une des revendications 4 à 8, **caractérisé en ce que** le recuit d'homogénéisation à l'étape (iv) est effectué pendant une durée d'au moins 30 minutes.

10. Le procédé selon l'une des revendications 4 à 9, **caractérisé en ce que** le refroidissement à l'étape (v) est effectué dans l'eau, de préférence à température ambiante.

11. Le procédé selon l'une des revendications 4 à 10, **caractérisé en ce qu'**à l'étape (vi), les processus de formage sont effectués par laminage à froid de l'alliage refroidi.

12. Le procédé selon la revendication 11, **caractérisé en ce que** le laminage à froid à l'étape (vi) est effectué jusqu'à une réduction d'au moins 50 % de l'épaisseur du matériau, de préférence de 50 à 80 % de l'épaisseur du matériau.

13. Le procédé selon la revendication 11 ou 12, **caractérisé en ce que** le recuit de recristallisation à l'étape (vii) est effectué à une température entre 810 et 830°C, de préférence de 820°C, et le refroidissement est effectué selon l'étape (viii) dans un four, de

préférence à une vitesse d'au moins 1°C/min, ou dans l'air, de préférence à température ambiante.

14. Le procédé selon la revendication 11 ou 12, **caractérisé en ce que** le recuit de recristallisation à l'étape (vii) est effectué à une température supérieure à 882°C, de préférence à environ 950°C, et le refroidissement est effectué selon l'étape (viii) dans de l'eau.

15. Le procédé selon la revendication 13 ou 14, **caractérisé en ce que** le recuit de recristallisation à l'étape (vii) est effectué pendant une durée d'au moins 10 minutes, de préférence pendant une durée de 10 minutes.

16. Le procédé selon l'une des revendications 4 à 10, **caractérisé en ce qu'**à l'étape (vi), les processus de formage sont réalisés par forgeage à chaud au-dessus de la température de transition α -> β.

17. Utilisation des alliages ternaires selon l'une quelconque des revendications 1 à 3 pour la production d'éléments porteurs de constructions légères et/ou d'éléments critiques fonctionnant à des températures élevées, de préférence des soupapes, des bielles, des arbres et/ou des éléments structurels, de préférence des corps, des collecteurs d'évacuation des gaz d'échappement et/ou des éléments de gainage de moteur et/ou des entraînements et/ou des aubes et/ou des commandes de turbines à gaz.

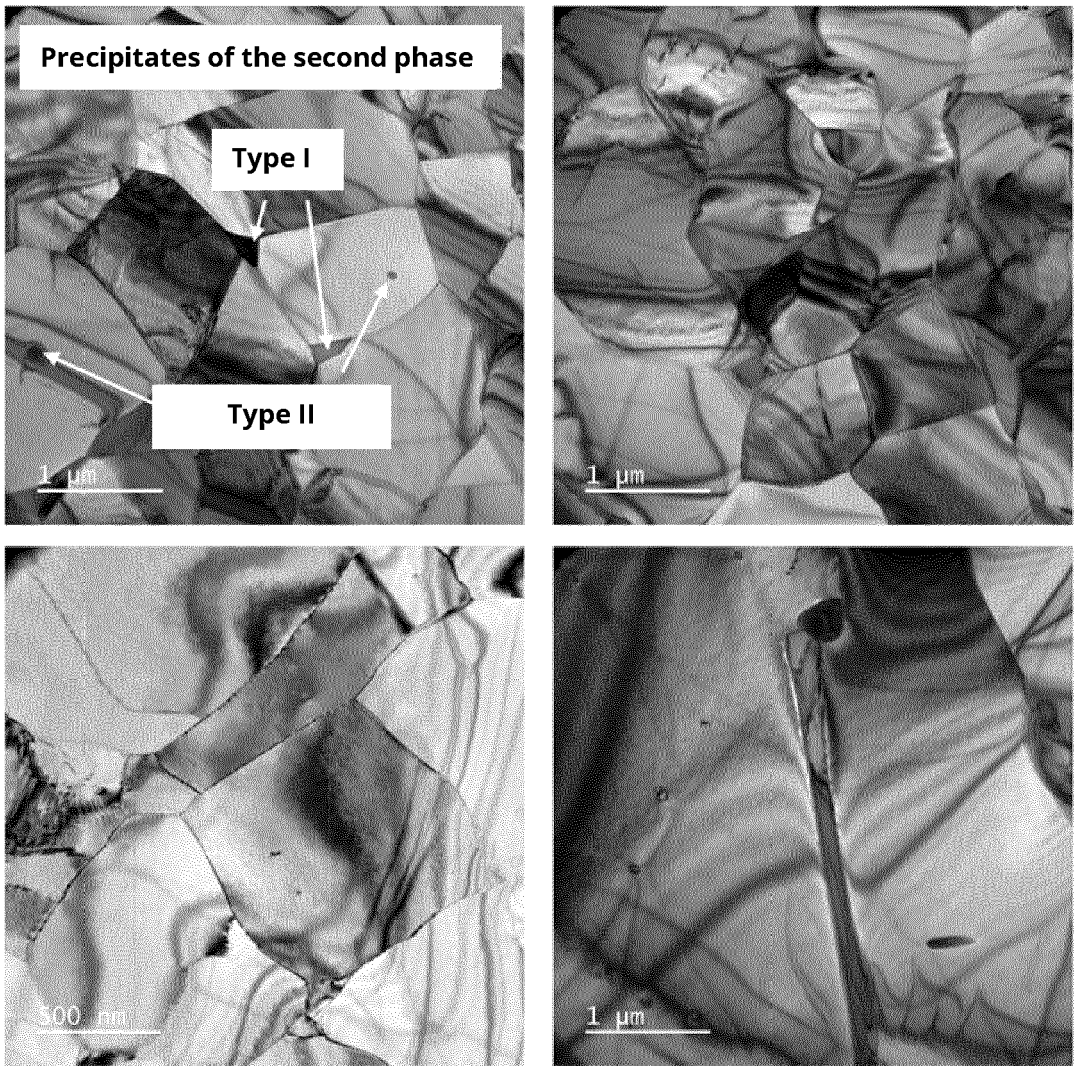

Precipitates of the second phase
Type I
Type II
1 μm
1 μm
500 nm
1 μm

Fig. 1

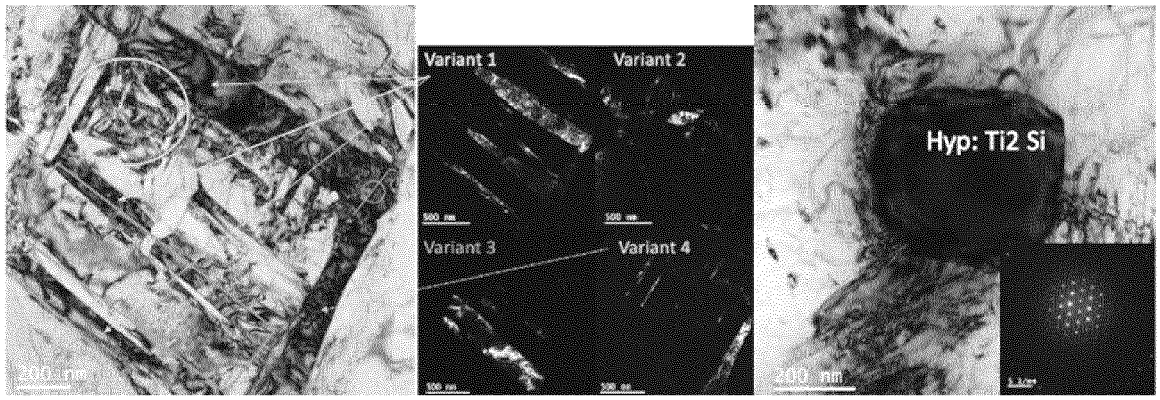

Variant 1
Variant 2
Variant 3
Variant 4
Hyp: Ti2 Si
200 nm

Fig. 2

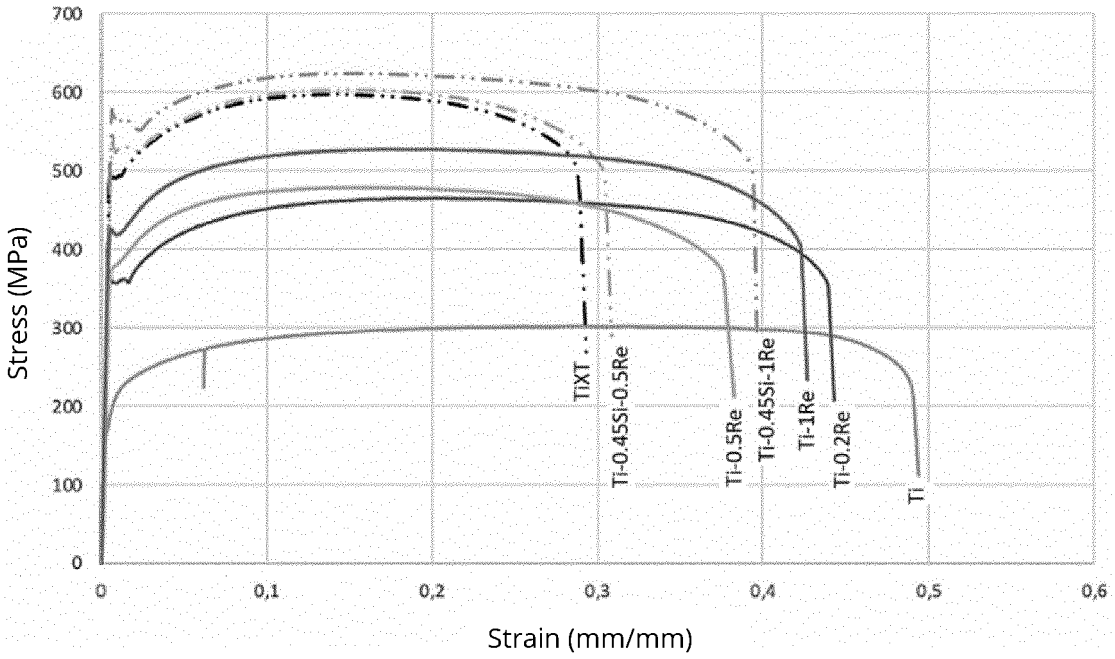
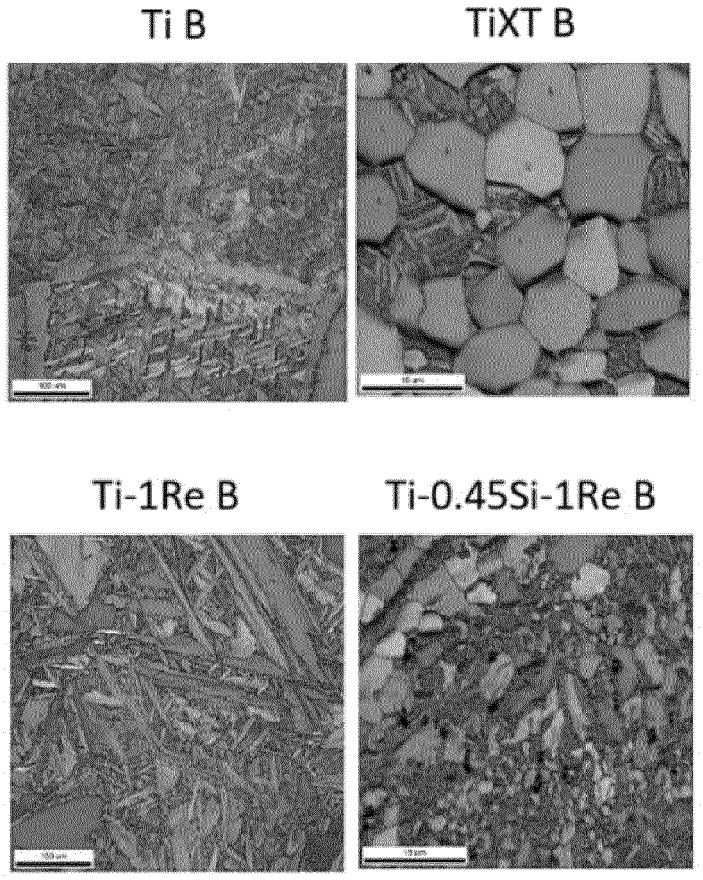

700
600
500
400
300
200
100
0
Stress (MPa)
0
0,1
0,2
0,3
0,4
0,5
0,6
Strain (mm/mm)
TiXT
Ti-0.45Si-0.5Re
Ti-0.5Re
Ti-0.45Si-1Re
Ti-1Re
Ti-0.2Re
Ti

Fig. 3

a)


Ti B
TiXT B
Ti-1Re B
Ti-0.45Si-1Re B

b)

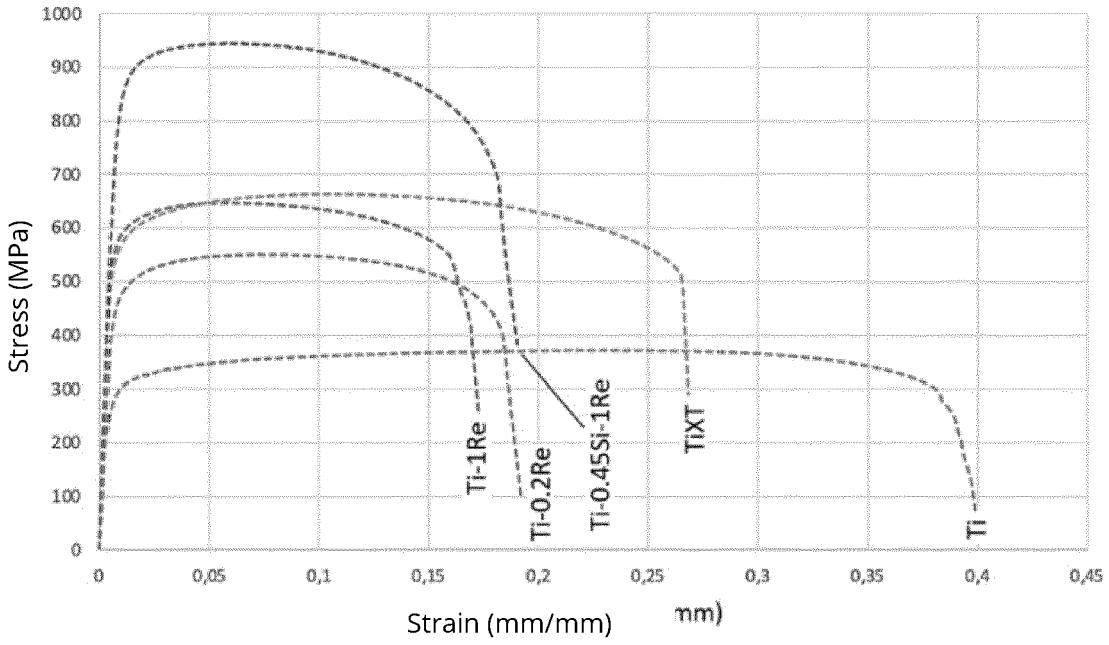

Stress (MPa)
Strain (mm/mm)
Ti-1Re
Ti-0.2Re
Ti-0.45Si-1Re
TiXT
Ti

Fig. 4

REFERENCES CITED IN THE DESCRIPTION

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