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(54) **METHOD OF MAKING A HIGH STRENGTH, HIGH TOUGHNESS, FATIGUE RESISTANT,
PRECIPITATION HARDENABLE STAINLESS STEEL**

VERFAHREN ZUR HERSTELLUNG EINES AUSSCHIEDUNGSHÄRTBAREN NICHTTROSTENDEN
STAHL MIT HOHER FESTIGKEIT, HOHER ZÄHIGKEIT UND DAUERFESTIGKEIT

PROCÉDÉ DE RÉALISATION D'UN ACIER INOXYDABLE DURCISSABLE PAR PRÉCIPITATION,
RÉSISTANT À LA FATIGUE, À RIGIDITÉ ET À RÉSISTANCE ÉLEVÉES

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EP 2 247 761 B1

Description**BACKGROUND OF THE INVENTION**5 **Field of the Invention**

[0001] This invention relates to a method of making precipitation-hardenable stainless steel alloys to reduce the size and distribution of inclusions that adversely affect the fatigue resistance and fracture toughness provided by such alloys.

10 **Description of the Related Art**

[0002] US Patent No. 5,681,528 and US Patent No. 5,855,844 describe high-strength, notch-ductile, precipitation-hardening stainless steels. Those alloys are used for structural applications in the aerospace industry and in many additional non-aerospace uses. Testing of the known alloys by the aerospace industry has indicated that the fatigue life provided by the alloys, while considered to be acceptable, leaves something to be desired. Fatigue life is a very important parameter for the design of aerospace structural members. Improved fatigue life would allow for either product weight savings or longer design service life for structural components. It is desired to provide improved fatigue-strength relative to the known alloys, while still maintaining the excellent combination of strength, toughness, and corrosion resistance that the known alloys provide.

20 **[0003]** The abovementioned fatigue testing has demonstrated that the majority of fatigue failures initiate at large second phase inclusions, which are present in the material as a result of the alloy composition and processing. The alloy made according to the present invention is designed to provide strength and toughness that are equivalent to the known alloy, but without the resultant large second phase inclusions that adversely affect the fatigue resistance of the known alloy.

25 **SUMMARY OF THE INVENTION**

[0004] The improvement in fatigue life desired for the known precipitation hardenable, stainless steel alloys is achieved to a large degree by making a high strength, high toughness, precipitation-hardenable stainless steel alloy by the method of claim 1 in accordance with a first aspect of the present invention.

30 **[0005]** The broad, intermediate, and preferred compositional ranges of the precipitation hardening, martensitic stainless steel used in the present invention are as follows, in weight percent:

		Broad	Intermediate	Preferred
35	C	0.03 max	0.02 max	0.015 max
	Mn	1.0 max	0.25 max	0.10 max
	Si	0.75 max	0.25 max	0.10 max
	P	0.040 max	0.015 max	0.010 max
	S	0.020 max	0.010 max	0.005 max
40	Cr	10-13	10.5-12.5	11.0-12.0
	Ni	10.5-11.6	10.75-11.25	10.85-11.25
	Ti	1.5-1.8	1.5-1.7	1.5-1.7
	Mo	0.25-1.5	0.75-1.25	0.9-1.1
	Cu	0.95 max	0.50 max	0.25 max
45	Al	0.25 max	0.050 max	0.025 max
	Nb	0.3 max	0.050 max	0.025 max
	B	0.010 max	0.001-0.005	0.0015-0.0035
	N	0.030 max	0.015 max	0.010 max

50 **[0006]** The balance of the alloy is iron except for the usual impurities found in commercial grades of such steels and minor amounts of additional elements which may vary from a few thousandths of a percent up to larger amounts that do not objectionably detract from the desired combination of properties provided by this alloy.

55 **[0007]** The foregoing tabulation is provided as a convenient summary and is not intended thereby to restrict the lower and upper values of the ranges of the individual elements of the alloy used in this invention for use in combination with each other, or to restrict the ranges of the elements for use solely in combination with each other. Thus, one or more of the element ranges of the broad composition can be used with one or more of the other ranges for the remaining elements

in the preferred composition. In addition, a minimum or maximum for an element of one preferred embodiment can be used with the maximum or minimum for that element from another preferred embodiment. Throughout this application percent (%) means percent by weight unless otherwise indicated. The term "inclusion" encompasses secondary particles and phases such as sulfides, oxides, oxysulfides, carbides, nitrides, and carbonitrides.

DETAILED DESCRIPTION

[0008] In the alloy made according to the present invention, the unique combination of strength, notch toughness, and stress-corrosion cracking resistance is achieved by balancing the elements chromium, nickel, titanium, and molybdenum. At least about 10%, better yet at least about 10.5%, and preferably at least about 11.0% chromium is present in the alloy to provide corrosion resistance commensurate with that of a conventional stainless steel under oxidizing conditions. At least about 10.5%, better yet at least about 10.75%, and preferably at least about 10.85% nickel is present in the alloy because it benefits the notch toughness of the alloy. At least about 1.5% titanium is present in the alloy to benefit the strength of the alloy through the precipitation of a nickel-titanium-rich phase during aging. At least about 0.25%, better yet at least about 0.75%, and preferably at least about 0.9% molybdenum is also present in the alloy because it contributes to the alloy's notch toughness. Molybdenum also benefits the alloy's corrosion resistance in reducing media and in environments which promote pitting attack and stress-corrosion cracking.

[0009] When chromium, nickel, titanium, and/or molybdenum are not properly balanced, the alloy's ability to transform fully to a martensitic structure using conventional processing techniques is inhibited. Furthermore, improper balancing of chromium, nickel, titanium, and molybdenum in this alloy impairs the alloy's ability to remain substantially fully martensitic when solution treated and age-hardened. Under such conditions the strength provided by the alloy is significantly reduced. Therefore, chromium, nickel, titanium, and molybdenum present in this alloy are restricted. More particularly, chromium is limited to not more than about 13%, better yet to not more than about 12.5%, and preferably to not more than about 12.0% and nickel is limited to not more than about 11.6% and preferably to not more than about 11.25%. Titanium is restricted to not more than about 1.8% and preferably to not more than about 1.7% and molybdenum is restricted to not more than about 1.5%, better yet to not more than about 1.25%, and preferably to not more than about 1.1%.

[0010] Sulfur in this alloy tends to combine with manganese and/or titanium to form manganese sulfides (MnS) and/or titanium sulfides (TiS) which adversely affect the fracture toughness, notch toughness, and notch tensile strength of the alloy. A product form of this alloy having a large cross-section, i.e., $>0.7 \text{ in}^2$ ($>4 \text{ cm}^2$), does not undergo sufficient thermomechanical processing to homogenize the alloy and neutralize the adverse effect of the sulfide inclusions. A small addition of calcium is preferably made to the alloy to benefit the fatigue strength of the alloy by combining with sulfur to facilitate the removal of sulfur from the alloy. In the known alloy, small additions of cerium, lanthanum, and/or other rare earth metals are used to benefit the toughness and fracture toughness properties, especially in large section sizes. However, although the use of such rare earth treatment benefits the toughness of the alloy, it has now been found that remnants of such rare earth inclusions may also serve as crack initiation sites that adversely affect the fatigue strength of the alloy. Therefore, rare earth additions are not used in the present alloy so as to avoid the presence of the rare earth inclusions. Rare earth metals including cerium, lanthanum, yttrium, etc. are restricted such that the combined amounts of such elements are not more than about 0.001%. Preferably, the alloy contains not more than about 0.0008%, and better yet not more than 0.0007% of such elements.

[0011] The elimination of the rare earth treatment would have been expected to adversely affect the fracture toughness of the alloy, especially in larger section sizes. However, it has been found that the use of the calcium treatment instead of the rare earth treatment not only benefits the fatigue strength of the alloy, but does not adversely affect the combination of toughness and fracture toughness provided by this alloy. Therefore, it is believed that the alloy made according to the present invention provides strength and toughness equivalent to the known alloys.

[0012] Additional elements such as boron, aluminum, niobium, manganese, and silicon may be present in controlled amounts to benefit other desirable properties provided by this alloy. More specifically, up to about 0.010% boron, better yet up to about 0.005% boron, and preferably up to about 0.0035% boron can be present in the alloy to benefit the hot workability of the alloy. In order to provide the desired effect, at least about 0.001 % and preferably at least about 0.0015% boron is present in the alloy.

[0013] Aluminum and/or niobium can be present in the alloy to benefit the yield and ultimate tensile strengths. More particularly, up to about 0.25%, better yet up to about 0.10%, still better up to about 0.050%, and preferably up to about 0.025% aluminum can be present in the alloy. Also, up to about 0.3%, better yet up to about 0.10%, still better up to about 0.050%, and preferably up to about 0.025% niobium can be present in the alloy. Although higher yield and ultimate tensile strengths are obtainable when aluminum and/or niobium are present in this alloy, the increased strength is developed at the expense of notch toughness. Therefore, when optimum notch toughness is desired, aluminum and niobium are restricted to the usual residual levels.

[0014] Up to about 1.0%, better yet up to about 0.5%, still better up to about 0.25%, and preferably up to about 0.10%

manganese and/or up to about 0.75%, better yet up to about 0.5%, still better up to about 0.25%, and preferably up to about 0.10% silicon can be present in the alloy as residuals from scrap sources or deoxidizing additions. Such additions are beneficial when the alloy is not vacuum melted. Manganese and/or silicon are preferably kept at low levels because of their deleterious effects on toughness, corrosion resistance, and the austenite-martensite phase balance in the matrix material.

[0015] The balance of the alloy is iron apart from the usual impurities found in commercial grades of alloys intended for similar service or use. The levels of such elements are controlled so as not to adversely affect the desired properties.

[0016] In particular, too much carbon and/or nitrogen impair the corrosion resistance and deleteriously affect the toughness and fatigue strength provided by this alloy. Accordingly, not more than about 0.03%, better yet not more than about 0.02%, and preferably not more than about 0.015% carbon is present in the alloy. Also, not more than about 0.030%, better yet not more than about 0.015%, and preferably not more than about 0.010% nitrogen is present in the alloy. When carbon and/or nitrogen are present in larger amounts, the carbon and/or nitrogen combines with titanium to form titanium-rich non-metallic inclusions, such as titanium carbonitrides. That reaction inhibits the formation of the nickel-titanium-rich phase which is a primary factor in the high strength provided by this alloy. Moreover, such carbonitrides serve as crack-initiation sites and adversely affect the fracture toughness and fatigue resistance provided by the alloy.

[0017] Phosphorus is maintained at a low level because of its deleterious effect on toughness and corrosion resistance. Accordingly, not more than about 0.040%, better yet not more than about 0.015%, and preferably not more than about 0.010% phosphorus is present in the alloy.

[0018] Not more than about 0.020%, better yet not more than about 0.010%, and preferably not more than about 0.005% sulfur is present in the alloy. Larger amounts of sulfur promote the formation of titanium-rich non-metallic inclusions which, like carbon and nitrogen, inhibit the desired strengthening effect of the titanium and serve as crack-initiation sites that adversely affect the fracture toughness and fatigue resistance provided by the alloy. Also, greater amounts of sulfur deleteriously affect the hot workability and corrosion resistance of this alloy and impair its toughness, particularly in a transverse direction. Oxygen is limited to not more than about 25 parts per million (ppm). Tramp elements such as lead, bismuth, antimony, arsenic, tellurium, selenium, tin, germanium, and gallium are limited to about 0.003% max. each, better yet to not more than about 0.002% each, and preferably to not more than about 0.001% each.

[0019] Too much copper deleteriously affects the notch toughness, ductility, and strength of this alloy. Therefore, the alloy contains not more than about 0.95%, better yet not more than about 0.75%, still better, not more than about 0.50%, and preferably not more than about 0.25% copper.

[0020] The method according to the present invention is preferably carried out by vacuum induction melting (VIM) the constituent elements as described above. Preferably, VIM is followed by vacuum arc remelting (VAR), but other practices can be used. The preferred method of providing calcium in this alloy is through the addition of a nickel-calcium compound during VIM. The nickel-calcium compound, such as the Ni-Cal® alloy sold by Chemalloy Co. Inc., is added in an amount effective to combine with available phosphorus, sulfur, and oxygen. Other techniques for adding calcium may also be used. For example, capsules of elemental calcium or calcium master alloys can be added to the melt. It is believed that a slag containing calcium or a calcium compound may also be used. The chemical reactions result in the formation of secondary phase inclusions such as calcium sulfides, calcium oxides, and calcium oxysulfides that can be readily removed during primary or secondary melting. It is believed that any residual calcium-based inclusions are sparsely dispersed in the alloy matrix material upon solidification. It is expected that after VAR the alloy contains less than about 0.001 % calcium and not more than about 0.001 % sulfur. The inclusions are generally smaller in major cross-sectional size than the rare-earth-based inclusions and Ti-rich non-metallic inclusions that are present in the known alloys. It is also believed that the size distribution of the calcium-based inclusions is about 0.5 μm to about 3.00 μm in major cross-sectional dimension, when such inclusions are present. The very small size and sparse dispersion of Ca-based inclusions benefits the strength, toughness, and fatigue resistance provided by the alloy.

[0021] This alloy can be made using powder metallurgy techniques, if desired. Although the alloy of the present invention can be hot or cold worked, cold working enhances the mechanical strength of the alloy.

[0022] The precipitation hardening alloy made in the present invention is solution annealed and then age hardened to develop the desired high strength and hardness. The solution annealing temperature should be high enough to dissolve essentially all of the undesired precipitates into the alloy matrix material. However, if the solution annealing temperature is too high, it will impair the fracture toughness of the alloy by promoting excessive grain growth. Typically, the alloy of the present invention is solution annealed at about 1700°F-1900°F (927°C-1038°C) for about 1 hour and then quenched.

[0023] When desired, this alloy can also be subjected to a deep chill treatment after it is quenched, to further develop the high strength of the alloy. The deep chill treatment cools the alloy to a temperature sufficiently below the martensite finish temperature to ensure the completion of the martensite transformation. Typically, a deep chill treatment consists of cooling the alloy to below about -100°F (-73°C) for about 1 to 8 hours. The need for a deep chill treatment will be affected, at least in part, by the martensite finish (M_F) temperature of the alloy. If the M_F temperature is sufficiently high, the transformation to a martensitic structure will proceed without the need for a deep chill treatment. In addition, the need for a deep chill treatment may also depend on the cross-sectional size of the piece being manufactured. As the

size of the piece increases, segregation in the alloy becomes more significant and the use of a deep chill treatment becomes more beneficial. Further, the length of time that the piece is chilled may need to be increased for large pieces in order to ensure that the transformation to martensite is completed. For example, it has been found that in a piece having a large cross-sectional area as described above, a deep chill treatment lasting about 8 hours is preferred for developing the high strength that is characteristic of this alloy.

[0024] The alloy made in the present invention is age hardened in accordance with techniques used for the known precipitation hardening, stainless steel alloys, as are known to those skilled in the art. For example, the alloys are aged at a temperature between about 900°F (482°C) and about 1150°F (621°C) for about 4 to 8 hours. The specific aging conditions used are selected by considering that: (1) the ultimate tensile strength of the alloy decreases as the aging temperature increases; and (2) the time required to age harden the alloy to a desired strength level increases as the aging temperature decreases.

Claims

1. A method of making a precipitation hardenable, high strength, high toughness, stainless steel alloy comprising the steps of:

melting a martensitic steel alloy having the following composition in weight percent, about

Carbon	0.03 max.
Manganese	1.0 max.
Silicon	0.75 max.
Phosphorus	0.040 max.
Sulfur	0.020 max.
Chromium	10-13
Nickel	10.5-11.6
Titanium	1.5-1.8
Molybdenum	0.25-1.5
Copper	0.95 max.
Aluminum	0.25 max.
Niobium	0.3 max.
Boron	0.010 max.
Nitrogen	0.030 max.

and the balance being iron and usual impurities;
 adding calcium to the alloy while molten whereby the calcium combines with available sulfur and oxygen to form calcium-based inclusions selected from the group consisting of calcium sulfides, calcium oxides, calcium oxysulfides, and combinations thereof;
 processing said alloy to remove at least a portion of said calcium-based inclusions; and then
 solidifying said alloy;

whereby rare earth metal additions are not used in the alloy, and after said processing and solidifying steps said alloy contains substantially no rare-earth based inclusions and any residual calcium-based inclusions are sparsely dispersed in the alloy.

2. The method as claimed in Claim 1 wherein the melting step comprises vacuum melting the martensitic steel alloy and the adding step is performed during said vacuum melting.
3. The method as claimed in Claim 2 wherein the processing step comprises vacuum remelting the alloy.
4. The method as claimed in Claim 1 wherein the processing step comprises vacuum remelting the alloy.
5. The method claimed in any of Claims 1 to 4 wherein the melting step comprises melting a martensitic steel alloy having the following composition in weight percent, about

EP 2 247 761 B1

5	Carbon	0.02 max.
	Manganese	0.25 max.
	Silicon	0.25 max.
	Phosphorus	0.015 max.
	Sulfur	0.010 max.
	Chromium	10.5-12.5
10	Nickel	10.75-11.25
	Titanium	1.5-1.7
	Molybdenum	0.75-1.25
	Copper	0.50 max.
	Aluminum	0.050 max.
15	Niobium	0.050 max.
	Boron	0.001-0.005
	Nitrogen	0.015 max.

and the balance being iron and usual impurities.

6. The method claimed in any of Claims 1 to 4 wherein the melting step comprises melting a martensitic steel alloy having the following composition in weight percent, about

25	Carbon	0.015 max.
	Manganese	0.10 max.
	Silicon	0.10 max.
	Phosphorus	0.010 max.
	Sulfur	0.005 max.
30	Chromium	11.0-12.0
	Nickel	10.85-11.25
	Titanium	1.5-1.7
	Molybdenum	0.9-1.1
	Copper	0.25 max.
35	Aluminum	0.025 max.
	Niobium	0.025 max.
	Boron	0.0015-0.0035
	Nitrogen	0.010 max.

and the balance being iron and usual impurities.

Patentansprüche

1. Verfahren zur Herstellung einer ausscheidungshärtbaren Edelstahllegierung mit hoher Festigkeit und hoher Zähigkeit, das die folgenden Schritte umfasst:

das Schmelzen einer Martensitstahllegierung mit einer Zusammensetzung in Gewichtsprozent von jeweils etwa:

50	Kohlenstoff:	max. 0,03
	Mangan:	max. 1,0
	Silicium:	max. 0,75
	Phosphor:	max. 0,040
55	Schwefel:	max. 0,020
	Chrom:	10 bis 13
	Nickel:	10,5 bis 11,6

EP 2 247 761 B1

(fortgesetzt)

Titan:	1,5 bis 1,8
Molybdän:	0,25 bis 1,5
Kupfer:	max. 0,95
Aluminium:	max. 0,25
Niob:	max. 0,3
Bor:	max. 0,010
Stickstoff:	max. 0,030

wobei der Rest Eisen und gewöhnliche Verunreinigungen sind;
das Zusetzen von Calcium zu der Legierung, während sie geschmolzen ist, wodurch das Calcium sich mit dem verfügbaren Schwefel und Sauerstoff vereinigt und so aus der aus Calciumsulfiden, Calciumoxiden, Calciumoxysulfiden und Kombinationen daraus bestehenden Gruppe ausgewählte calciumbasierte Einschlüsse bildet;
das Prozessieren der Legierung, um zumindest einen Teil der calciumbasierten Einschlüsse zu entfernen; und dann
das Verfestigen der Legierung;
wobei keine Seltenerdmetallzusätze in der Legierung verwendet werden, nach den Schritten des Prozessierens und Verfestigens die Legierung im Wesentlichen keine auf seltenen Erden basierenden Einschlüsse enthält und etwaige zurückbleibende calciumbasierte Einschlüsse in der Legierung spärlich dispergiert sind.

2. Verfahren nach Anspruch 1, worin der Schritt des Schmelzens das Vakuumschmelzen der Martensitstahllegierung umfasst und der Schritt des Zusetzens während des Vakuumschmelzens erfolgt.
3. Verfahren nach Anspruch 2, worin der Schritt des Prozessierens das neuerliche Vakuumschmelzen der Legierung umfasst.
4. Verfahren nach Anspruch 1, worin der Schritt des Prozessierens das neuerliche Vakuumschmelzen der Legierung umfasst.
5. Verfahren nach einem der Ansprüche 1 bis 4, worin der Schritt des Schmelzens das Schmelzen einer Martensitstahllegierung mit einer Zusammensetzung in Gewichtsprozent von jeweils etwa:

Kohlenstoff:	max. 0,02
Mangan:	max. 0,25
Silicium:	max. 0,25
Phosphor:	max. 0,015
Schwefel:	max. 0,010
Chrom:	10,5 bis 12,5
Nickel:	10,75 bis 11,25
Titan:	1,5 bis 1,7
Molybdän:	0,75 bis 1,25
Kupfer:	max. 0,50
Aluminium:	max. 0,050
Niob:	max. 0,050
Bor:	0,001 bis 0,005
Stickstoff:	max. 0,015

wobei der Rest Eisen und gewöhnliche Verunreinigungen sind, umfasst.

6. Verfahren nach einem der Ansprüche 1 bis 4, worin der Schritt des Schmelzens das Schmelzen einer Martensitstahllegierung mit einer Zusammensetzung in Gewichtsprozent von jeweils etwa:

Kohlenstoff:	max. 0,015
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EP 2 247 761 B1

(fortgesetzt)

Mangan:	max. 0,10
Silicium:	max. 0,10
Phosphor:	max. 0,010
Schwefel:	max. 0,005
Chrom:	11,0 bis 12,0
Nickel:	10,85 bis 11,25
Titan:	1,5 bis 1,7
Molybdän:	0,9 bis 1,1
Kupfer:	max. 0,25
Aluminium:	max. 0,025
Niob:	max. 0,025
Bor:	0,0015 bis 0,0035
Stickstoff:	max. 0,010

wobei der Rest Eisen und gewöhnliche Verunreinigungen sind, umfasst.

Revendications

1. Procédé de fabrication d'un alliage d'acier inoxydable durcissable par précipitation, à résistance élevée, à rigidité élevée, comprenant les étapes de :

faire fondre un alliage d'acier martensitique ayant la composition suivante en pour cent en poids, d'environ

carbone	0,03 max.
manganèse	1,0 max.
silicium	0,75 max.
phosphore	0,040 max.
soufre	0,020 max.
chrome	10-13
nickel	10,5 11,6
titane	1,5-1,8
molybdène	0,25-1,5
cuivre	0,95 max.
aluminium	0,25 max.
niobium	0,3 max.
bore	0,010 max.
azote	0,030 max.

et le reste étant du fer et des impuretés usuelles ;

ajouter du calcium à l'alliage pendant qu'il est à l'état de fusion moyennant quoi le calcium se combine avec le soufre et l'oxygène disponible pour former des inclusions basées sur le calcium sélectionnées dans le groupe consistant en sulfures de calcium, oxydes de calcium, oxysulfures de calcium et leurs combinaisons ;

traiter ledit alliage pour supprimer au moins une portion desdites inclusions basées sur le calcium ; et ensuite solidifier ledit alliage ;

où des additions de métaux de terres rares ne sont pas utilisées dans l'alliage, et après lesdites étapes de traitement et de solidification, ledit alliage ne contient sensiblement pas d'inclusions basées sur des terres rares, et d'éventuelles inclusions résiduelles basées sur le calcium sont peu densément dispersées dans l'alliage.

2. Procédé selon la revendication 1, dans lequel l'étape de fusion comprend la fusion sous vide de l'alliage d'acier martensitique, et l'étape d'addition est exécutée durant ladite fusion sous vide.

EP 2 247 761 B1

3. Procédé selon la revendication 2, dans lequel l'étape de traitement comprend la refusion sous vide de l'alliage.

4. Procédé selon la revendication 1, dans lequel l'étape de traitement comprend la refusion sous vide de l'alliage.

5 5. Procédé selon l'une quelconque des revendications 1 à 4, dans lequel l'étape de fusion comprend la fusion d'un alliage d'acier martensitique ayant la composition suivante en pour cent en poids, d'environ

	carbone	0,02 max.
	manganèse	0,25 max.
10	silicium	0,25 max.
	phosphore	0,015 max.
	soufre	0,010 max.
	chrome	10,5-12,5
15	nickel	10,75 11,25
	titane	1,5-1,7
	molybdène	0,75-1,25
	cuivre	0,50 max.
	aluminium	0,050 max.
20	niobium	0,50 max.
	bore	0,001-0,005 max.
	azote	0,015 max.

25 et le reste étant du fer et des impuretés usuelles.

6. Procédé selon l'une quelconque des revendications 1 à 4, dans lequel l'étape de fusion comprend la fusion d'un alliage d'acier martensitique ayant la composition suivante en pour cent en poids, d'environ

	carbone	0,15 max.
	manganèse	0,10 max.
	silicium	0,10 max.
	phosphore	0,010 max.
	soufre	0,005 max.
35	chrome	11,0-12,0
	nickel	10,85 11,25
	titane	1,5-1,7
	molybdène	0,9-1,1
40	cuivre	0,25 max.
	aluminium	0,025 max.
	niobium	0,025 max.
	bore	0,015-0,0035 max.
45	azote	0,010 max.

et le reste étant du fer et des impuretés usuelles.

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REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 5681528 A [0002]
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