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2,918,367

TITANIUM BASE ALLOY

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This invention relates to titanium base alloys, and more particularly, to a unique titanium-aluminum-vanadium or molybdenum-silicon alloy having superior properties, and to a method of preparing alloys having superior properties and consisting of titanium-aluminum-vanadium or molybdenum, with or without silicon.

Although titanium based alloys have been known for several years, such alloys have in most cases possessed properties which left something to be desired in one respect or another. In general, they tended to lack the requisite combinations of strength and ductility and/or combinations of tensile strength and impact strength for toughness. Also, such alloys appeared to be unable to retain high strength at high temperatures or to retain ductility (particularly under "creep" conditions) at high temperatures. The formability properties of such alloys also left something to be desired, particularly when alloy formulations giving a high ultimate strength were desired.

According to the instant invention it has been discovered that valuable alloys, suitable for structural purposes and the like, having superior low temperature properties and also superior high temperature strength can be produced by the use in combination of aluminum, silicon and vanadium and/or molybdenum in a titanium base, which is a polyphase alloy consisting primarily of the alpha form or phase of titanium together with at least one other distinct microcrystalline phase that is known as the beta form of titanium.

Another feature of the instant invention involves a special heat treating process for the instant alloys (containing silicon) and also for titanium-aluminum-molybdenum alloys of the type heretofore known and described, for example, in Jaffee and Ogden U.S. Patent No. 2,554,031. If the titanium-molybdenum-aluminum alloys described in said U.S. Patent No. 2,554,031 (not treated in accordance with the teachings of the instant invention) are subjected to creep conditions at elevated temperatures, such alloys are likely to become brittle because of their metallurgical condition. This tendency toward embrittlement has heretofore limited greatly the utility of the titanium-aluminum-molybdenum alloys; but the special heat treating process of the instant invention substantially completely overcomes this tendency toward embrittlement.

It is, therefore, an important object of the instant invention to provide an improved titanium based alloy and an improved method of forming stable titanium based alloys.

It is a further object of the instant invention to provide an improved titanium-aluminum-vanadium or molybdenum-silicon alloy having superior physical and metal-

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lurgical properties at low and high temperatures; and an improved method of forming the same.

It is yet another object of the instant invention to provide an improved method of stabilization heat treating for titanium-aluminum-molybdenum alloys (which may optionally contain silicon).

Other objects, features and advantages of the present invention will become apparent to those skilled in the art from the following detailed disclosure thereof.

10 The instant invention consists in an improved alloy composed essentially of 2% to 8% of aluminum, 2% to 6% of a metal from the class consisting of vanadium, molybdenum and mixtures thereof, 0.1% to 1.5% of silicon, balance titanium. Process-wise, the instant invention also consists in an improved method of stabilization treatment for the alloy just mentioned or for a corresponding titanium-aluminum-molybdenum alloy containing no silicon, which comprises the steps of, first, deliberately coarsening the microstructure of the alloy by holding 20 the alloy at an elevated temperature in the polyphase field for a sufficient period of time, then, quickly cooling the coarsened alloy and, finally, aging the alloy at an elevated temperature below the coarsening temperature until the beta phase becomes dark etching.

25 The titanium base metal used in the present alloys may, of course, contain substances, impurities, or the so-called "interstitial contaminants" such as carbon, oxygen and/or nitrogen which are found in either high purity titanium or commercially pure titanium. The titanium used may be commercial titanium such as may be produced by a magnesium-reduction process of the type described in Kroll U.S. Patent No. 2,205,854; or the titanium used may be a high purity or "iodide" process titanium such as may be produced in accordance with the teachings of 30 Van Arkel U.S. Patent No. 1,671,213; provided that the various impurity contents are such as to avoid appreciable alternation of the advantageous physical and metallurgical properties of the instant alloy. In general, the amount of oxygen in the alloy may range from a mere trace quantity (i.e., about 0.01%) up to about 0.1-0.2%. (As used herein, the terms "percent" and "parts" mean percent and parts by weight, unless otherwise designated, and the percents here given are based on the final alloy weight.) The amount of nitrogen in the alloy may range 35 from a mere trace amount (i.e., about 0.005%) up to 0.1%. The amount of carbon in the alloy may range from a mere trace amount (i.e., about 0.01%) up to 0.25%; and the total oxygen, nitrogen and carbon contents should not exceed about 0.5%, if the alloys are to possess the superior physical and metallurgical properties herein obtained.

40 As is known, the "scavenger" properties of titanium at high temperatures permit titanium to take up appreciable quantities of various materials, other than the inert gases, and formation of the instant alloy is thus carried out under conditions which tend to exclude such various materials and ingredients which are readily combined with titanium. In the practice of the instant invention, the instant alloy is preferably "double arc melted" in the presence of an inert atmosphere such as argon; and this is done by first compacting a comminuted metal composition having the desired formulation, in the form of a suitable electrode, which is melted by the arc formed 45 using such electrode, and the resulting ingot is employed

a second time as an arc-forming electrode which is re-melted. It will be appreciated that other known methods may be used for compounding the instant alloy, such as by hot rolling suitable sintered and unsintered powdered metal compacts in a suitable protective atmosphere.

One contaminant which has been found to be of distinct importance is hydrogen, and it is particularly desirable to prepare the instant alloy in the substantial absence of hydrogen, since excessive amounts of hydrogen in the instant alloy tend to impair the physical and metallurgical properties thereof, or at least to subtract noticeably from the superior properties characteristic of the instant alloy. The amount of hydrogen in the alloy may range from mere trace amounts (i.e., about 0.001%) up to 0.02-0.03%. Most preferably, the hydrogen content in the alloy is not more than 0.02%.

As indicated, the amount of aluminum in the instant alloy may range from a minimum effective amount for appreciably increasing the strength, of about 2% of the alloy, to a maximum amount of aluminum, of about 8% of the alloy, which may be used without tending to cause excessive brittleness in the alloy. A preferred range is about 4% to about 6% aluminum in the alloy. Even narrower ranges for the amount of aluminum are preferred in the case of certain specific uses, which will be described hereinafter.

As previously mentioned, the amounts of vanadium, molybdenum or mixtures thereof used in the practice of the instant invention may range from a minimum amount of about 1% or 2% at which improvements in strength and formability are noticeable to a maximum of about 6%, above which no appreciable benefits are apparently obtained in the alloy of the instant invention. It appears that the desirable properties here obtained in the alloy by the addition of vanadium or molybdenum indicate that molybdenum in small amounts is somewhat more effective than vanadium, so that an appreciable effect is obtained using as little as 1% molybdenum whereas a comparable effect requires approximately 2% vanadium. It is ordinarily advisable to use vanadium (alone) within the range of 4% to 6%, and most preferably 3% to 5%; whereas it is advisable to use molybdenum (alone) in the instant alloy within the range of about 1% to 5%, and preferably 3% to 4%.

An advantageous aspect of the instant invention resides in the use of relatively small amounts of silicon to improve strength properties, and particularly high temperature strength properties, without appreciably impairing the formability of the alloy. For example, the strength properties increase with increasing amounts of aluminum and to a lesser extent with increasing amounts of vanadium and/or molybdenum. The formability of the alloy, however, tends to decrease with increasing amounts of aluminum; and the formability will increase with increasing amounts of vanadium and/or molybdenum. A 7% aluminum-3% molybdenum-remainder titanium alloy has appreciably greater strength than a 6% aluminum-3% molybdenum-remainder titanium alloy, but it also has poor formability (or greater resistance to hot working particularly). The difference in formability is of critical industrial significance, requiring different working techniques, temperatures, dies, etc., merely because of a change of 1% in the aluminum content (from 6% to 7% aluminum). On the other hand, the improvement in strength is also of industrial importance and is of a magnitude to make it significant. In the practice of the instant invention, however, it is possible to approximate the high temperature strength of the 7% aluminum alloy just described by adding ½% silicon to the 6% aluminum-3% molybdenum-remainder titanium alloy just described, without appreciably impairing the hot formability of this alloy. The silicon addition is relatively small since excessive amounts thereof would tend to cause embrittlement in the alloy and the maximum practical amount of silicon which might be used in the instant alloy for

obtaining improved high temperature strength without imparting undesirable properties to an unnecessary extent is about 1.5%, and preferably about ½% to 1%. The minimum amount of silicon which may be used to obtain an appreciable improvement in the instant invention is about 0.1%, with the preferred range for the silicon content being 0.3-0.5%.

Alloy compositions of 6% aluminum, 4% vanadium, ½% silicon, remainder titanium and 6% aluminum, 3% molybdenum, ½% silicon, remainder titanium have been found to be of particular industrial significance.

As previously mentioned, the preferred method for compounding the instant alloy is double arc melting and the resulting alloy may be hot rolled at, for example, 1400-1700° F. or hot forged at, for example, 1500-2000° F. A unique feature of the instant alloys, as well as certain titanium-aluminum-molybdenum alloys (which will be described), is the response of these alloys to a certain heat treating procedure, which brings about an unusual alteration in the properties of the alloys reducing or substantially eliminating their tendency toward embrittlement under creep conditions at elevated temperatures. Moreover, the heat treating procedure is itself unusual in that the initial step involves coarsening of the alloy microstructure, which is in direct contrast to the accepted techniques for the handling of titanium base alloys.

As has been explained hereinbefore, the instant alloys are polyphase alloys in that they consist primarily of the alpha form of titanium (at room temperatures) together with at least one other distinct microcrystalline phase that is known as the beta form of titanium. Heating of the alloy to extremely high temperatures will result in the substantially complete conversion to a single microcrystalline phase (presumably the beta phase); but the various heat treating procedures herein described do not involve heating this high or, in other words, heating above the polyphase field. Also, it is known generally that heating to an elevated temperature in the polyphase field, and holding at this temperature for an appreciable period of time, will initiate coarsening of the microstructure. Such coarsening is well understood by those skilled in the art and it involves, among other things, an increase in the average interlamellar spacing in the microstructure. Coarsening is a metallurgical phenomenon which is peculiar with respect to the factor of time. Merely heating to a temperature at which coarsening should take place is not sufficient to effectively initiate coarsening. Instead, it is necessary to hold the alloy at this temperature for an appreciable period of time (i.e., an appreciable "incubation" period) which may be required in order to obtain the necessary energy balance in the alloy to actually initiate coarsening. Coarsening then takes place more or less as a function of the time (after once initiated). In general, the prior art teachings in connection with titanium base alloys make certain references to "annealing" at an elevated temperature under conditions which will effect recrystallization, but not substantial "grain growth" or re-solution of carbides. A typical description appears in Jaffee, Ogden and Maykuth U.S. Patent No. 2,596,489, wherein annealing is carried out by "soaking at a temperature of about 850° C. for about 3½ hours." This procedure is described as being effective for recrystallization, but not substantial grain growth. In the alloys of the instant invention, the alpha phase is ordinarily present to a substantial extent and additional phases such as the beta phase appear as dispersed grains or lamellae in the microstructure (with the alpha phase providing the "interlamellar" spacing). Coarsening is evidenced by an increase in the average spacing and ultimately results in the formation of a continuous alpha phase. Although it is not desired to limit the invention to any particular theory, it is believed that the formation of the continuous alpha phase during the coarsening procedure is of importance since this pro-

vides an "envelope" of alpha titanium around discrete beta phase particles and a complete alpha titanium matrix in which the beta phase particles are dispersed. The alpha phase is believed to possess elasticity such as to permit higher ductility in the alloy and the alpha phase is particularly effective in this capacity when it is the continuous phase. The initial step in the instant heat treating procedure thus involves coarsening the microstructure of the alloy to form a continuous and coarse alpha phase. This condition does not result from the ordinary alloy formation procedures (i.e., double arc melting and the like) nor does this condition result from working the alloy, for example, by rolling or forging. Furthermore, the teachings of the prior art caution against holding the alloy at an effective temperature for a period sufficient to initiate coarsening, to say nothing of carrying out coarsening to the extent necessary to form a continuous alpha phase. In general, coarsening is carried out at least to the extent necessary to effect doubling of the average interlamellar spacing in the microstructure, and preferably, to effect about a 300-500% increase in the average spacing.

As previously mentioned, the above identified titanium-aluminum-vanadium or molybdenum-silicon alloy may be used in the instant heat treatment, or a titanium-aluminum-molybdenum alloy such as that described in said U.S. Patent No. 2,554,031 may be used. The titanium-aluminum-molybdenum alloy which may be used may contain 2% to 8% aluminum, and preferably 6% to 7% aluminum. The molybdenum content of this alloy may range from 2% to 6% and is preferably 2% to 4%. Specific embodiments include 7% aluminum-3% molybdenum-remainder titanium and 6% aluminum-3% molybdenum-remainder titanium.

In a preferred embodiment of the instant process, coarsening is carried out at about 1500° F. to about 1650° F. for a period of time within the range of about 4 hours to about 24 hours. As mentioned, the coarsening heat treatment of this step forms a continuous alpha phase in the alloy.

Next, the alloy is quickly cooled and the cooling of the coarsened alloy may be carried out in an inert atmosphere, or in air, or it may be carried out by quenching the alloy. Various rapid cooling methods are well understood by those skilled in the art; and the instant cooling may be carried out to approximately room temperature (followed by a reheat for the subsequent aging step) or the cooling may involve merely dropping the temperature of the alloy to the temperature at which aging takes place in the final heat treating step. The aging process may be referred to as a stabilizing process and it involves maintaining the alloy at approximately the temperature of application, which temperature in the case of heat resistant alloys of principal interest that are here involved is in the neighborhood of at least about 1000° F. Preferably, the aging is carried out within the range of approximately 1000-1200° F., which is slightly above the application temperatures ordinarily contemplated (which usually are in the range of about 800° F. to about 1000° F.). The aging is carried out until a dark etching beta phase is formed. Specifically, the etchant used is 60 cc. of glycerine, 20 cc. of concentrated nitric acid, and 20 cc. of concentrated hydrofluoric acid; and aging is carried out until the beta phase is dark etching in response to the application of this etchant. Etching techniques generally are well understood by those skilled in the art and need not be described in further detail herein and it should also be noted that etching is used in metallurgy to ascertain certain changes taking place in the microcrystal structure. In the instant case the length of time for aging is measured on the basis of conversion of the beta phase to a dark etching phase. Ordinarily, aging at temperatures of 1000° F. to 1200° F. for about 4 hours to about 24 hours is desirable.

Specific embodiments of the instant invention are shown in the attached tables:

TABLE 1A

Alloy	Intended Composition in Weight Percent (Balance Titanium)				Heat Treatment
	Al	Mo	V	Si	
A	6	1		0.5	1,110° F.—24 hrs.—A.C. 1,560° F.—24 hrs.—WQ, 1,020° F.—48 hrs.—A.C.
B	6	2		0.5	1,110° F.—24 hrs.—A.C. 1,560° F.—24 hrs.—WQ, 1,020° F.—48 hrs.—A.C.
C	6	3		0.5	1,110° F.—24 hrs.—A.C. 1,560° F.—24 hrs.—WQ, 1,020° F.—48 hrs.—A.C.
D	6		4	0.5	1,110° F.—24 hrs.—A.C. 1,560° F.—24 hrs.—WQ, 1,020° F.—48 hrs.—A.C.
E	6	1		0.5	1,560° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.
F	6	2		0.5	1,560° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.
G	6	3		0.5	1,650° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.
H	6		4	0.5	1,560° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.
J	6	2		0.5	1,560° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.
K	6	3		0.5	1,650° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.

30 F.C.—furnace cool.
A.C.—air cooled.
WQ—water quenched.

TABLE 1B

Tensile properties of Ti-Al-Mo-Si and Ti-Al-V-Si alloys

Alloy	Ultimate Tensile Strength (p.s.i.)	Yield Strength (0.2% offset) (p.s.i.)	Reduction in Area, percent	Elongation in 1 inch, percent	Modulus of Elasticity 10 ⁶ , p.s.i.	Diamond Pyramid Hardness (20 Kg. load)
A	{ 140,300 140,000	{ 128,300 127,700	{ 27.2 29.6	{ 11.5 15	{ 17.5 17.6	{ 342 -----
B	{ 156,000 155,300	{ 136,000 134,300	{ 15.2 25.0	{ 11.5 12	{ 19.0 17.0	{ 331 -----
C	{ 154,000 163,500	{ 144,300 138,000	{ 13.6 15.4	{ 6 8	{ 17.0 18.0	{ 352 -----
D	{ 155,000 146,000	{ 137,500 138,000	{ 11.5 21.8	{ 9 10	{ 16.0 15.5	{ 337 -----
AT 1,020° F.						
E	78,800	62,000	52.0	15	11.7	-----
F	79,800	58,630	57.0	18	15.0	-----
G	93,800	70,700	53.0	16.5	14.0	-----
H	87,000	59,800	44.2	16.5	11.9	-----
AT 1,200° F.						
J	76,500	42,000	60.2	22	10.3	-----
K	72,200	35,100	64.4	20	14.2	-----

TABLE 2A

Alloy	Intended Composition, Weight Percent (Balance Titanium)				Heat Treatment
	Al	Mo	V	Si	
L	6	1		0.5	1,560° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.
M	6	2		0.5	1,560° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.
N	6	3		0.5	1,650° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.
O	6		4	0.5	1,560° F.—24 hrs.—A.C, 1,020° F.—48 hrs.—A.C.

75 A.C.—air cool.

TABLE 2B

Creep-rupture properties of Ti-Al-Mo-Si and Ti-Al-V-Si alloys

Alloy	Test Temperature, ° F.	Rupture Stress, p.s.i.		Stress to Give Minimum Creep Rate	
		100 Hrs.	500 Hrs.	0.1%/Hr.	0.01%/Hr.
L	1,020	52,000	42,000		
M	1,020	52,000	42,000		
N	1,200	13,000			
	1,020	57,000	46,000	62,000	40,000
O	1,200	19,000	12,000		
	1,020	40,000	31,500		

TABLE 3A

Alloy	Intended Composition, Weight Percent (Balance Titanium)				Heat Treatment
	Al	Mo	V	Si	
P	6	1		0.5	1,560° F.—24 hrs.—AC, 1,020° F.—48 hrs.—AC.
Q	6	2		0.5	1,560° F.—24 hrs.—AC, 1,020° F.—48 hrs.—AC.
R	6	3		0.5	1,650° F.—24 hrs.—AC, 1,020° F.—48 hrs.—AC.
S	6		4	0.5	1,560° F.—24 hrs.—AC, 1,020° F.—48 hrs.—AC.

TABLE 3B

Stability of room temperature tensile properties of Ti-Al-Mo-Si and Ti-Al-V-Si alloys upon exposure to creep at elevated temperatures

Alloy	Exposure Conditions				Before Exposure			After Exposure		
	Temp., ° F.	Stress, p.s.i.	Time, Hrs.	Def. (1''), Percent	Ultimate Tensile Strength, p.s.i.	RA, Percent	Elong. (1''), Percent	Ultimate Tensile Strength, p.s.i.	RA, Percent	Elong. (1''), Percent
P	1,020	15,000	501.5	0.0	140,000	29.6	15.0	134,200	6.0	3.0
Q	1,020	15,000	501.6	0.0	155,300	25.0	12.0	142,200	18.2	8.0
	1,200	5,000	500.4	1.0	155,300	25.0	12.0	131,800	11.6	6.0
R	1,020	15,000	503.8	0.0	152,500	16.8	11.0	156,400	11.9	8.5
	1,200	5,000	520.7	0.5	152,500	16.8	11.0	141,200	15.5	10.0
S	1,020	10,000	500.0	0.0	146,000	21.8	10.0	149,500	10.9	8.0

TABLE 4A

Alloy	Condition of Ti—7% Al—3% Mo Alloy
T	As-forged-water quenched (unstable).
U	Aged 1,020° F.—24 hrs.—AC.
V	Part 1—Coarsening anneal only: 1,575° F.—24 hrs.—WQ.
W	Coarsening anneal and age No. 1: 1,470° F.—6 hrs.—WQ, 1,020° F.—48 hrs.—AC.
X	Coarsening anneal and age No. 2: 1,575° F.—24 hrs.—WQ, 1,020° F.—48 hrs.—AC.
Y	Coarsening anneal and age No. 2 followed by exposure to 1,020° F. for 1,001 hours under a stress of 20,000 p.s.i.
Z	Coarsening anneal and age No. 3: 1,575° F.—24 hrs.—WQ, 1,200° F.—48 hrs.—AC, followed by exposure to 1,200° F. for 1,001 hours under a stress of 6,000 p.s.i.

TABLE 4B

Application of special two-part stabilizing heat treatment 1 to Ti—7% Al—3% Mo alloy for elevated temperature application

Alloy	Ultimate Tensile Strength, p.s.i.	Yield Strength (0.2% Offset), p.s.i.	Reduction in Area, Percent	Elong. in 1'', Percent	Modulus of Elasticity, 10 ⁶ p.s.i.	Diamond Pyramid Hardness (20 Kg. Coal)
T	153,000	131,300	27.0	13	17.1	333
U	151,000	138,000	9.3	7.5	17.5	357
V	149,000	77,000	42.5	18.8	12.8	313
W	151,000	132,000	17.5	11.2	19.1	363
X	161,000	134,000	26.2	15.0	16.6	365
Y	159,200	134,900	28.0	15		
Z	138,000	122,000	14.9	11		

1 Two-part stabilizing heat treatment consists of (1) a coarsening anneal high in the α - β field and (2) an aging treatment at a lower temperature to stabilize the β phase.

It will be understood that modifications and variations may be effected without departing from the scope of the novel concepts of the present invention.

I claim as my invention:

- 5 1. A method of preparing a stable alloy for high temperature use that is composed essentially of 2% to 8% of aluminum, 2% to 6% of a metal from the class consisting of vanadium, molybdenum and mixtures thereof, 0.1% to 1.5% of silicon, balance titanium, wherein the aluminum content is at least as great as that of said metal,
- 10 which comprises the steps of holding the alloy at an elevated temperature in the polyphase field for a period of time sufficient to coarsen the microstructure forming a continuous alpha phase, quickly cooling the coarsened alloy, and then aging the alloy at an elevated temperature below the coarsening temperature until the beta phase becomes dark etching.
- 15 2. A method of preparing a stable alloy for high temperature use that is composed essentially of 2% to 8% of aluminum, 2% to 6% of a metal from the class consisting of vanadium, molybdenum and mixtures thereof,
- 20 0.1% to 1.5% of silicon, balance titanium, wherein the aluminum content is at least as great as that of said metal, which comprises the steps of holding the alloy at 1500-1650° F. for a period of time sufficient to coarsen the microstructure forming a continuous alpha phase,
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45 quickly cooling the coarsened alloy, and then aging the alloy at 1000-1200° F. until the beta phase becomes dark etching.

3. A method of preparing a stable alloy for high temperature use that is composed essentially of 2% to 8% of aluminum, 2% to 6% of a metal from the class consisting of vanadium, molybdenum and mixtures thereof,

50 0.1% to 1.5% of silicon, balance titanium, wherein the aluminum content is at least as great as that of said metal, which comprises the steps of holding the alloy at an elevated temperature in the polyphase field high in the polyphase field for a period of time sufficient to coarsen the microstructure forming a continuous alpha phase so that the average interlamellar spacing in the microstructure is at least doubled, quickly cooling the coarsened alloy, and then aging the alloy at an elevated temperature below the coarsening temperature until the beta phase becomes dark etching.

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4. A method of preparing a stable alloy for high temperature use that is composed essentially of 4% to 6% of aluminum, 3% to 5% of vanadium, 0.3% to 0.5% of silicon, balance titanium, the titanium containing up to 0.02% H, wherein the aluminum content is at least as great as that of the vanadium, which comprises the steps of holding the alloy at an elevated temperature in the polyphase field for a period of time sufficient to coarsen the microstructure forming a continuous alpha phase, quickly cooling the coarsened alloy, and then aging the alloy at an elevated temperature below the coarsening temperature until the beta phase becomes dark etching.

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5. A method of preparing a stable alloy for high tem-

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perature use that is composed essentially of 4% to 6% of aluminum, 3% to 4% of molybdenum, 0.3% to 0.5% of silicon, balance titanium, the titanium containing up to 0.02% H, wherein the aluminum content is at least as great as that of the molybdenum, which comprises the steps of holding the alloy at an elevated temperature in the polyphase field for a period of time sufficient to coarsen the microstructure forming a continuous alpha phase, quickly cooling the coarsened alloy, and then aging the alloy at an elevated temperature below the coarsening temperature until the beta phase becomes dark etching.

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