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TITANIUM BASE ALLOYS

Robert I. Jaffee, Worthington, and Horace R. Ogden and Daniel J. Maykuth, Columbus, Ohio, assignors, by mesne assignments, to Rem-Cru Titanium, Inc., Midland, Pa., a corporation of Pennsylvania

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This invention pertains to strong, ductile and thermally stable, titanium-base alloys containing as essential constituents, aluminum, together with one or more of the elements selected from the group consisting of vanadium, columbium and tantalum.

The aluminum content may range from about 0.5 to 8% and the metal of the group vanadium, columbium and tantalum may range from about 0.5 to 40% and preferably from about 0.5 to 15% in aggregate, the aluminum content being on the low side of its range when the metal of the vanadium, columbium, tantalum group is on the high side of its range, and vice versa.

The alloys of the invention containing about 5 to 15% vanadium undergo marked age hardening on solution treating at about 700 to 800° C. and thereafter aging at about 300 to 600° C. The preferred aging heat treatment for most analyses comprises a solution treatment at about 700–750° C. followed by aging at about 500° C.

This application is a continuation-in-part of our copending application Serial No. 326,776, filed December 17, 1952, which is in turn a continuation-in-part of our application Serial No. 209,903, filed February 7, 1951, now abandoned, and which is in turn a continuation-in-part of our application Serial No. 151,314, filed March 22, 1950, now abandoned, and is also a continuation-in-part of our copending applications Serial No. 356,096, filed May 19, 1953, and Serial No. 409,252, filed February 9, 1954, both now abandoned.

As is known, the metal titanium in the pure state, assumes at temperatures below about 885° C. or 1625° F., a close-packed hexagonal microstructure known as the alpha phase, while at this temperature and above, it assumes a body-centered cubic structure known as the beta phase.

Certain substitutional alloying additions to the titanium base metal, among which may be mentioned aluminum, indium, antimony, tin, bismuth, lead, thallium, cadmium, zinc and silver, as well as the interstitials, carbon, oxygen and nitrogen, tend to stabilize the alpha phase.

Other substitutional alloying elements, when added in progressively increasing quantities, stabilize the beta phase at progressively lower temperatures, until a mixed-phase, alpha-beta or a stable all-beta microstructure is obtained at normal or atmospheric temperatures, or the beta phase undergoes a eutectoid reaction, depending on the character and amount of the beta stabilizers added.

Speaking in broadest terms, the beta stabilizers are

Mn, Mo, Cr, Fe, V, W, Cb, Ta, Ni, Co, Si, Be, Zr and Cu. Within this broad category, however, only certain of the elements mentioned are suitable for producing mixed-phase, alpha-beta alloys or all-beta alloys. These are the elements which form with titanium, beta-isomorphous systems or which have beta-eutectoid systems such that the decomposition of the beta phase into eutectoid is so sluggish that the alloys behave like those in a beta-isomorphous system. The beta stabilizing elements of this type are V, Mo, Cb, Ta, Mn, Cr and Fe. Within this group, however, only Mo, V, Cb and Ta are beta-isomorphous. They form the most thermally stable beta-containing alloys, as a result of this beta-isomorphism.

It will be observed, therefore, that in the alloys of the present invention, the aluminum functions as an alpha-promoter or stabilizer while the metal of the group vanadium, columbium and tantalum functions as a beta-promoter or stabilizer. And since all of the elements of this group, namely, vanadium, columbium and tantalum, form, as above noted, beta-isomorphous systems with titanium, they, together with molybdenum, are the most desirable beta-promoters to be employed for producing mixed-phase, alpha-beta or all-beta alloys of titanium.

The all-alpha, all-beta and mixed-phase, alpha-beta alloys of titanium have their respective advantages and disadvantages. Generally speaking, the alpha alloys provide good all-around performance, having good weldability, and being strong and resistant to oxidation, both hot and cold, but are somewhat inferior as to ductility. The all-beta alloys, on the other hand, have excellent bendability and ductility, are strong both hot and cold, but somewhat vulnerable to atmospheric contamination, particularly at elevated temperatures. The mixed-phase, alpha-beta alloys provide a compromise performance as between all-alpha and all-beta alloys, being strong when cold and warm, but weak hot, while possessing good bendability and ductility with a moderate degree of resistance to atmospheric contamination.

The alloys of the present invention are all of the mixed-phase, alpha-beta or all-beta types, depending on the total amount of beta-promoters present. Within the range of about 0.5 to 10% or 12% of beta-promoters, the alloys are in general found to be of the mixed-phase, alpha-beta structure with the many advantages associated with such alloys, including fair tolerance for carbon, oxygen or nitrogen, which tolerance is not present in the all-beta alloys. With higher additions of beta-promoters, the alloys are of the unstable or stable all-beta type, although the zone between the two is not definitely demarked.

For the all-beta alloys of the invention, namely, those containing high total content of beta-promoters, the aggregate content of the interstitials, carbon, oxygen and nirogen, should be kept under about 0.2% maximum. For the mixed-phase, alpha-beta alloys, i. e., those containing under about 10 or 12% of beta-promoters, the carbon tolerance increases to a maximum of about 0.5%, and there may also be present up to about 0.2% of either or both oxygen and nitrogen, for extremely low additions of the beta-isomorphous group metals referred to.

As above stated, the alloys of the invention are all characterized in a high degree of thermal stability, and

in being easily stabilized thermally, i. e., put into a condition such that they will not become embrittled by prolonged exposure to high temperatures. They also have excellent welding characteristics, in that they may be welded without appreciably reducing the ductility in the welded portions as compared to the non-welded portions.

As shown below, additions of the eutectoid-forming, beta-promoting elements aforesaid, particularly those which decompose sluggishly, may be made to the basic titanium-aluminum beta-isomorphous-containing alloys, of the invention without unduly impairing their excellent thermal stability characteristics. Thus, for example, up to about one-half of the aggregate content of the beta-isomorphous elements present may be replaced by the sluggishly decomposing element chromium, or up to about one-quarter by the somewhat less sluggishly decomposing elements manganese or iron, or up to about one-eighth by the relatively rapidly decomposing beta-promoters such as W, Cu, Ni, Co, Si, Be, as above mentioned.

Also, up to about one-half of the alpha-promoting aluminum content may be replaced by other alpha-promoters on an equivalent basis. On a replacement basis, for example, about 3% of the alpha-promoters antimony or tin, is equivalent to about 1% aluminum.

The following Table I gives test results on the room temperature mechanical properties and also the thermal stability characteristics of representative ternary titanium-base alloys according to the invention. All of the alloys thus tested were prepared by forging at 1800° F., followed by rolling at 1500° F. to 0.08", then descaled, again rolled at 1400° F. to 0.04", held 15 minutes at 1400° F., furnace cooled therefrom to 1100° F., held one hour thereat, air cooled thence to room temperature and descaled before testing. Also in Table I, "Commercial Purity Ti-Base" refers to titanium metal of commercial purity as produced by the magnesium reduction of titanium tetrachloride in accordance with the process described in the Kroll Patent 2,205,854, while "Iodide Base" refers to titanium metal of high purity as produced by the "iodide" process described in the patent to Van Arkel 1,671,213.

TABLE I

Mechanical and aging properties of ternary Ti–Al–beta-isomorphous alloys

Composition, Percent (Balance Titanium)		Tensile Prop., p. s. i. × 1,000		Percent Elongation in 1"	Percent Reduction in Area	VHN	Min. Bend Rad. T			
							As Rolled and Annealed		As Aged 48 Hrs. at 750° F.	
Al	V	0.2% Offset Yield	Ultimate Strength				L	T	L	T
		(Commercial Purity Ti-Base)								
------	------	48	71	21	51	187	0.8	0.8	----	----
4	------	96	106	19	51	319	219	5.7	2.5	2.8
2	6	91	110	9	33	267	1.2	1.5	2.4	1.7
4	2	101	116	12	35	291	2.4	2.3	2.4	2.4
4	2.5	96	106	19	51	319	2.9	5.7	2.5	2.8
4	5	110	120	15	39	309	2.9	5.0	3.5	4.5
4	10	114	121	10	29	265	1.6	3.2	1.5	5.1
4	15	111	124	8	30	281	0	2.2	1.1	6.8
5	5	128	133	9	44	----	4.0	>4.9	3.0	>4.0
4.8	5.7	127	132	19	46	----	3.8	>4.5	2.8	>4.2
[1] 0.5	30	102	107	10	26	234	1.0	1.0	4.0	6.8
[1] 0.5	40	107	111	10	33	255	0	0	0.5	1.4
Al	Cb									
4	2.5	88	97	20	51	309	2.3	2.8	2.1	2.9
4	5	94	104	19	53	317	2.7	2.8	2.8	2.9
4	10	124	133	13	47	339	3.2	5.5	3.4	5.3
[1] 0.5	30	71	98	20	33	222	0	0.8	Br	Br
Al	Ta									
4	5	85	93	23	51	306	2.4	2.4	1.9	1.9
4	10	89	98	20	52	317	2.4	2.0	1.8	1.9
4	15	95	102	19	50	327	3.0	2.6	2.0	1.9
[1] 0.5	30	71	74	15	31	215	0.5	1.0	1.5	1.6
Al	Ta	(Iodide Base)								
------	------	27	43	40	61	105	----	0	----	----
5	1	65	79	19	41	300	----	0.7	----	----
5	2.5	67	80	18	45	276	----	0.0	----	----
5	5	69	81	18	43	294	----	1.1	----	----
7.5	2.5	93	98	17	38	320	----	6.7	----	----

[1] Rolled at 1,550° F., annealed ¼ hr. at 1,550° F. and quenched.

The following Table II gives data corresponding to that of Table I for various quaternary titanium-base alloys according to the invention, containing in addition to aluminum and at least one element of the beta-isomorphous group, also another beta-promoter selected from the beta-isomorphous and eutectoid beta-promoter groups. The headings in Table II have the same significance as in Table I.

TABLE II

Mechanical and aging properties of quaternary Ti–Al–beta-isomorphous-containing alloys

Composition, Percent (Balance Titanium)	Tensile Prop. p. s. i. × 1,000		Percent Elongation in 1"	Percent Reduction in Area	VHN	Min. Bend Rad. T	
	0.2% Offset Yield	Ultimate Strength				As Rolled and Annealed	As Aged 48 Hrs. at 750° F.
						L	L
4Al-5V-1.5Fe	141	150	10	36	356	2.2	1.7/3.5
4Al-5V-2.5Mn	145	150	5	33	343	2.8	2.4
4Al-5V-2.5Mo	140	144	11	40	353	2.9	3.0
4Al-5V-2.5Cr	138	146	9	28	338	2.4	2.8
4Al-5V-2.5W	151	154	6	30	367	2.7	3.6
4Al-5V-5Cb	150	152	5	33	335	5.4	3.4
4Al-5V-5Ta	144	145	6	33	351	2.8	3.3
4Al-5V-2Ni	132	144	5	14	341	6.9	Br
4Al-5V-2Co	154	160	5	27	368	2.3	2.0
4Al-5V-2.5Cu	133	139	1	16	346	3.6	3.0
4Al-5Cb-1.5Fe	135	143	11	41	330	2.1	2.3
4Al-5Cb-2.5Mn	144	148	7	38	337	2.5	3.6
4Al-5Cb-2.5Mo	135	141	9	25	350	3.5	2.8
4Al-5Cb-2.5Cr	139	145	11	37	353	2.4	3.7
4Al-5Cb-2.5W	119	132	9	39	349	2.3/6.5	2.1/10.4
4Al-5Cb-5Ta	121	127	15	44	325	2.7	2.6
4Al-5Cb-5V	150	152	5	33	335	5.4	3.4
4Al-5Cb-2Ni	114	124	6	25	311	3.7	3.9
4Al-5Cb-2Co	139	147	6	33	353	3.8	8.7
4Al-5Cb-2.5Cu	124	131	9	41	349	3.4	4.0
4Al-5Ta-1.5Fe	116	128	9	34	311	2.3	2.8
4Al-5Ta-2.5Mn	126	129	8	36	333	2.6	2.6
4Al-5Ta-2.5Mo	122	130	10	44	349	2.9	3.1
4Al-5Ta-2.5Cr	123	129	7	29	349	7.5/10.0	11.6
4Al-5Ta-2.5W	113	123	17	48	332	3.0	4.0
1Al-1V-4Fe	135	159	15		353		
2Al-2V-8Fe	182	193	6		348		
3Al-3V-12Fe					375	Br	
2Al-3V-5 each of Cr, Mn, Mo					294		
4Al-5Ta-5Cb	121	127	15	44	325	2.7	2.6
4Al-5Ta-5V	144	145	6	33	351	2.8	3.3
4Al-5Ta-2Ni	109	122	7	32	308	3.2	3.0
4Al-5Ta-2Co	108	127	4	26	330	7.1	8.7
4Al-5Ta-2.5Cu	110	117	11	40	348	4.1	2.9
3.8Al-2.5V-5.7Cr-0.3Mo	121	126	20	47		4.0	3.2

Comparing the test results of Tables I and II, it will be observed that whereas the ductility and thermal stability of the quaternary alloys are comparable to those of the ternary alloys, the tensile strength of the quaternary alloys is much higher than for the ternary alloys. Thus, whereas the offset yield and ultimate strength for the ternary, commercial purity titanium-base, alloys fall within ranges of about 85,000–125,000 and 95,000–135,000 p. s. i., respectively, the corresponding ranges for the quaternary alloys are about 110,000–150,000 and 125,000–160,000 p. s. i., respectively. On the average, therefore, the tensile strength is increased on the order of 25 to 30%. Thus, the presence in the alloy of a multiplicity of beta-promoters imparts a marked increase in strength with retention of adequate ductility and thermal stability as compared to the alloys containing but one beta-promoter.

It will be seen from the above data that the alloys in accordance with the invention have high tensile strengths as compared to the unalloyed titanium-base metal, being at least 10% in excess thereof in each instance, and that they combine this high strength with an extremely high degree of ductility, such as to permit of forming, both hot and cold, as by forging, rolling, etc. Also that the alloys have high thermal stability as evidenced by the aging tests showing that their ductilities are practically unchanged as compared to the as rolled and annealed condition.

As shown by the data in Tables I and II, the minimum bend ductilities for the various analyses range in general from about 1 to under 7, with corresponding elongations of about 5 to 25% for most analyses, showing that these alloys are quite ductile. Where the alloys are to be used in the form of sheets, however, the minimum bend ductilities may range as high as 20, and where the alloys are to be used in massive form, the percent tensile elongation may range as low as about 2%.

As above stated, the alloys of the invention containing about 5 to 15% vanadium are susceptible to appreciable age hardening on solution treating and subsequent aging in the temperature ranges aforesaid. This is shown by the test results in Table III below, made on specimens prepared and tested as follows:

Ingots weighing one-half pound each were prepared from titanium sponge of commercial purity and high purity vanadium and aluminum by arc melting the admixed starting ingredients in appropriate proportions, in a water-cooled copper crucible and in an inert or argon atmosphere. The initial ingots thus produced were inverted and again arc melted as aforesaid to assure the production of a homogeneous alloy. The ingots as thus produced were forged at 980° C., cleaned up and rolled at 760° C. into 0.01" sheet, then held at 780° C. one-half hour and furnace-cooled to 600° C. followed by air cooling to room temperature. Longitudinal bend test specimens were then sheared from these sheets and were given various solution anneals consisting of 8 hours at 650° C., 4 hours at 700° C., 2 hours at 750° C., and 1 hour at 800° C. followed by water quenching. All solution heat treatments as well as subsequent aging treatments were carried out under argon atmosphere with the specimens sealed in Vycor or Pyrex capsules. A specimen of each alloy in each of the above solution treated conditions plus a corresponding specimen fabricated as above described was then aged for 0, 1, 4 and 16 hours at 300° C., 400° C., 500° C. and 600° C. Surface Vickers hardness and minimum bend radius values were then determined for each of the specimens as thus heat treated with results as given in the following Table III.

TABLE III

Properties of age hardening Ti–Al–V alloys

Time, hours	Temp., C.	Heat Treatment Before Aging (Quenched from Temperature)									
		As Fabricated		8 Hr. at 650° C.		4 Hr. at 700° C.		2 Hr. at 750° C.		1 Hr. at 800° C.	
		VHN	MBR, T	VHN	MBR, T	VHN	MBR, T	VHN	MBR, T	VHN	MBR, T
		Ti–4Al–5V									
0		329	4.9	331	5.2	309	2.7	312	1.5	309	5.3
1	300	329	3.0	316	2.5	346	1.8	377	5.2	240	2.5
4	300	337	2.3	326	2.5	370	2.5	345	Br	342	4.7
16	300	344	2.5	321	2.3	373	3.1	377	3.3	352	2.8
1	400	355	2.3	326	2.3	376	4.7	352	2.5	368	2.5
4	400	350	2.5	331	4.9	359	5.9	360	2.4	382	3.1
16	400	337	1.5	333	2.6	374	1.3	384	2.6	391	2.4
1	500	317	2.4	329	2.8	322	2.3	354	3.7	378	4.6
4	500	347	2.4	338	2.4	348	2.7	364	4.8	372	2.6
16	500	342	2.4	329	2.4	348	3.3	365	2.5	373	2.5
1	600	345	3.3	333	2.8	332	2.7	316	2.4	345	2.5
4	600	343	2.3	328	1.7	335	2.4	358	2.4	348	4.7
16	600	333	1.5	331	1.7	230	2.5	323	1.7	331	2.5
		Ti–4Al–10V									
0		341	2.5	318	4.6	313	5.0	308	V Br	296	5.3
1	300	348	4.2	314	1.5	415	4.7	411	V Br	359	2.5
4	300	357	4.8	315	3.1	417	2.8	447	6.6	380	13.9
16	300	355	5.2	321	3.2	446	4.7	455	V Br	378	4.9
1	400	342	2.5	328	4.9	412	6.4	450	V Br	416	Br
4	400	345	2.4	327	2.4	359	10	416	5.3	455	Br
16	400	362	4.8	333	5.8	418	5.0	442	V Br	493	V Br
1	500	350	4.9	333	2.3	352	2.3	377	4.6	444	V Br
4	500	339	2.4	339	2.6	370	5.0	395	2.7	417	Br
16	500	334	1.7	339	1.5	365	2.5	410	4.7	409	11
1	600	346	6.6	328	4.7	319	4.7	343	4.7	367	4.8
4	600	341	4.7	326	1.5	339	12	333	2.4	352	4.7
16	600	331	2.5	335	2.5	335	Br	337	2.5	343	4.9
		Ti–4Al–15V									
0		332	2.7	322	4.9	316	V Br	299	4.7	319	V Br
1	300	360	4.6	323	6.2	314	2.2	313	V Br	317	2.9
4	300	351	4.9	322	2.3	316	1.9	353	4.7	420	Br
16	300	356	1.5	334	2.2	314	2.2	332	4.3	471	V Br
1	400	355	Br	344	2.5	322	4.3	428	Br	473	V Br
4	400			336	6.4	358	Br	414	8.7	488	Br
16	400	385	2.4	355	4.4	496	12.1	453	V Br	515	V Br
1	500	345	5.9	343	Br	354	Br	396	4.3	425	
4	500	343	4.7	345	4.2	366	1.7	392	4.7	429	V Br
16	500	351	2.2	357	4.6	382	4.4	395	13	434	11
1	600	329	Br	342	9.6	322	6.2	355	8.9	374	12.5
4	600	343	4.9	339	Br	340	4.8	335	5	369	6.1
16	600	336	2.8	325	Br	324	Br	327	Br	341	4.8

It will be seen from the above data that these Ti–Al–(5–15)V alloys undergo marked hardening on solution treating and aging at appropriate temperatures and for appropriate times, varying with the alloy analysis. It will further be noted that, in many instances, the age hardening is accompanied by an actual improvement in bend ductility as compared to the solution treated condition, and that in general the bend ductility as aged is well below the useful upper limit of about 20T for these alloys in sheet form. The following Table IV gives a few examples illustrative of the above and selected from Table III.

TABLE IV

Composition (Balance Ti)	Solution Treatment, C.	Aging Treatment		As Solution Treated		As Aged	
		Hr.	C	VHN	MBR, T	VHN	MBR, T
4Al–5V	700 Q	16	300	310	2.7	375	3.1
	800 Q	4–16	400	310	5.3	380–390	2.5–3
4Al–10V	700 Q	1–16	300	310	5	420–450	2.8–4.7
4Al–15V	700 Q	16	400	316	V Br	496	12.1
	750 Q	1–4	500	299	4.7	392–396	4.3–4.7

The following Table V gives for the alloys of Table III as well as for various other Ti–Al–V base alloys, the tensible properties, the Vickers hardness and the minimum bend ductility, for these alloys as solution treated and aged at the temperatures and for the times indicated. Included in this table are alloys wherein other beta stabilizers such as molybdenum and chromium are substituted for part of the vanadium at the five and ten percent total beta-stabilizer levels. Also included at the five and ten percent beta stabilizer levels, are the properties of the corresponding Ti–V alloys without aluminum. All test results in Table V were made on specimens fabricated into sheet as above outlined for the data of Table III.

TABLE V

Tensile properties of aged Ti–Al–V alloys

Solution Heat Treatment		Aging Heat Treatment		Tensile Properties, p. s. i. × 1,000		Percent Elongation in 1"	Percent Reduction in Area	VHN	MBR, T/L
Time, Hours	Temp., ° C.	Time, Hours	Temp., ° C.	0.2% Offset Yield	Ult. Str.				
		Ti–5V (RS–523–87)							
4	750			88	109	16	40	291	1.0
4	750	½	400	104	129	25	22	302	1.5
4	750	5	400					280	1.2
4	750	1	500	106	127	11	29	299	1.0
4	750	4	500	106	124	10	28	275	0.9
4	750	16	500	98	117	16	34	284	0.8
4	750	64	500	88	104	20	38	261	1.0
		Ti–4Al–5V (RS–523–55)							
4	750			94	133	16	29	272	1.5
4	750	½	400	122	145	10	28	324	2.1
4	750	5	400					329	2.1
4	750	1	500	129	155	10	33	362	2.5
4	750	4	500	127	146	14	27	343	2.7
4	750	16	500	132	150	9	25	346	1.7
4	750	64	500	133	145	11	11	324	2.0
		Ti–4Al–2.5V–2.5Mo (RS–523–64)							
4	750			130	146	8	25	328	2.1
4	750	½	400	132	143	8	28	358	3.2
4	750	5	400					343	2.1
4	750	1	500	139	152	8	26	339	2.0
4	750	4	500	138	154	7	23	340	3.6
4	750	16	500	148	164	7	23	374	3.0
4	750	64	500	147	160	5	15	352	2.5
		Ti–4Al–5V (RS–523–42)							
1	800			113	147	8	29	321	1.7
1	800	4	400	151	170	3	14	377	2.8
1	800	16	400	146	177	5	11	401	2.4
1	800	64	400	150	173	5	17	401	2.7
		Ti–10V (RS–523–88)							
4	700			163	168	0	6	379	2.7
4	700	½	400	163	171	2	3	455	>14.7
4	700	1	500	120	134	9	19	275	2.0
4	700	16	500	106	120	11	19	317	1.9
4	750			80	116	14	27	243	1.3
4	750	½	400	123	142	3	9	294	2.5/9.3
4	750	5	400					352	>13.4
4	750	1	500	160	180	3	5	352	13.6
4	750	4	500	138	152	7	16	317	2.5
4	750	64	500	115	126	6	31	290	2.0
		Ti–4Al–10V (RS–523–43)							
4	700			140	141	1	14	325	3.6
4	700	1	300	152	154	2	7	334	1.7
4	700	16	300	167	169	1	17	321	2.4
4	700	16	400	180	188	3	17	447	4.9
4	700	4	500	159	162	4	20		
4	700	16	500	166	170	5	24	382	2.6
		Ti–4Al–10V (RS–523–88)							
4	700			91	138	10	17	265	2.0
4	700	½	400	164	176	4	8	386	2.7
4	700	1	500	142	148	7	16	351	1.5
4	700	16	500	155	161	8	20	363	1.9
		Ti–4Al–10V (RS–523–57)							
4	750			66	132	10	25	259	1.3
4	750	½	400	172	200	3	1	375	5.7
4	750	5	400					408	>15.6
4	750	1	500	197	214	2	5	432	7.4
4	750	4	500	167	181	3	14	407	3.2
4	750	16	500	179	187	4	14	403	2.0
4	750	64	500	180	186	3	13	366	3.0

TABLE V—Continued

Solution Heat Treatment		Aging Heat Treatment		Tensile Properties, p. s. i. × 1,000		Percent Elongation in 1"	Percent Reduction in Area	VHN	MBR, T/L
Time, Hours	Temp., ° C.	Time, Hours	Temp., ° C.	0.2% Offset Yield	Ult. Str.				
		Ti-4Al-5V-5Cr (RS-523-67)							
4	700			135	140	11	22	322	0.4
4	700	½	400	144	148	12	20	325	0.4
4	700	1	500	165	175	10	18	378	1.5
4	700	16	500	161	168	7	18	382	1.6
4	750			130	138	9	20	297	2.0
4	750	½	400	188	190	3	16	456	>11.0
4	750	5	400					481	>11.5
4	750	1	500	189	209	5	14	470	4.3
4	750	4	500	197	208	7	9	386	3.0
4	750	16	500	190	202	5	13	454	9.9
4	750	64	500	191	195	2	3	416	>11.3
		Ti-4Al-5V-5Mo (RS-523-63)							
4	700			126	131	7	15	317	0.5
4	700	½	400	133	138	8	24	323	0.6
4	700	1	500	147	152	7	12	354	1.7
4	700	16	500	151	155	9	18	337	1.5
4	750			116	139	7	16	305	0
4	750	½	400	170	176	1	11	410	2.5
4	750	5	400					401	4.0/12.1
4	750	1	500	166	183	3	13	436	1.9
4	750	4	500	189	197	5	12	422	3.6
4	750	16	500	175	178	5	15	403	2.2/>13.5
4	750	64	500	161	166	5	17	392	2.4
		Ti-4Al-15V (RS-523-44)							
4	700			134	146	2	8	319	6.2
4	700	4	400	157	168	1	3	340	5.5
4	700	16	400	198	203	1	7	427	Br

It will be seen from the above data that whereas the Ti–5V binary alloy undergoes no appreciable hardening and strengthening as a result of the aging treatment, the addition of the aluminum introduces a marked hardening and strengthening action, accompanied by some loss of tensile elongation, but with practically no loss of bend ductility. Thus the optimum aging treatment increased the tensile strength of the Ti–4Al–5V specimens about 20,000 to 30,000 p. s. i. while retaining adequate tensile elongation for fabrication purposes and holding the minimum bend ductility value below about 3T.

At the ten percent beta stabilizer level the Ti–10V binary alloy has a relatively high tensile strength and zero tensile elongation as solution treated. Subsequent aging in general results in a considerable reduction in tensile strength accompanied by an increase in tensile elongation. The bend ductility is not materially influenced except for short time aging at about 400° C. which produces considerable embrittlement.

The addition of aluminum greatly reduces the strength and increases the ductility in the solution treated condition and also increases the spread between yield and ultimate strengths, thereby greatly facilitating the ease of fabrication and formability of the alloy in this condition. Thus the ternary Ti–4Al–10V alloy as a solution treated has a yield strength of 66,000–91,000 p. s. i. and an ultimate strength of 132,000–138,000 p. s. i. The tensile elongation is 10% and the bend ductility 1.3–2T. On aging the ultimate strength of this alloy may be increased up to about 190,000 p. s. i. with retention of a tensile elongation of at least 4% and a bend ductility not exceeding 2.0T, or up to about 215,000 p. s. i. with accompanying tensile elongation of 2.0% and bend ductility of 7.4T. As above stated, these alloys are useful in sheet form with bend ductilities as high as 20T and are useful as forgings with tensile elongations as low as 1 or 2%.

It will further be noted that the substitution of other beta stabilizers such as chromium or molybdenum for part of the vanadium, greatly increases the ductility of the as aged alloy without loss of strength.

As the beta stabilizer content is increased to the 15% level, the strengthening effect or aging remains high although accompanied by considerable loss in ductility.

The data in the foregoing tables, therefore, establishes that the alloys of the invention containing about 5–15% vanadium or the equivalent thereof, undergo tremendous strengthening on appropriate solution treating and aging with retention in general of adequate dutility. The tensile strengths ranging up to 200,000 p. s. i. and above class these age-hardened alloys among the strongest metals available.

The alloys of the invention may be made by melt casting in a cold mold, employing an electric arc in an inert atmosphere, or may be produced in other ways in which the alloy is rendered molten before casting.

What is claimed is:

1. A titanium-base alloy consisting essentially of about: 0.5 to 8% aluminum, 0.5 to 15% vanadium, carbon up to 0.5%, and up to a total of 0.2% of oxygen and nitrogen, balance substantially titanium characterized in having in the annealed condition, a minimum bend ductility of not more than 20T, a minimum tensile elongation of about 10%, a tensile strength at least 30% in excess of the unalloyed titanium base metal and a beta-containing microstructure.

2. A titanium-base alloy consisting essentially of about: 0.5 to 8% aluminum, 0.5 to 15% columbium, carbon up to 0.5%, and up to a total of 0.2% of oxygen and nitrogen, balance substantially titanium characterized in having in the annealed condition, a minimum bend ductility of not more than 20T, a minimum tensile elongation of about 10%, a tensile strength at least 30% in excess of the unalloyed titanium base metal and a beta-containing microstructure.

3. A titanium-base alloy consisting essentially of about: 0.5 to 8% aluminum, 0.5 to 15% tantalum, carbon up to 0.5%, and up to a total of about 0.2% of oxygen and

nitrogen, balance substantially titanium characterized in having in the annealed condition, a minimum bend ductility of not more than 2.5T, a minimum tensile elongation of about 10%, a tensile strength at least 30% in excess of the unalloyed titanium base metal and a beta-containing microstructure.

4. A titanium-base alloy consisting essentially of about: 0.5 to 8% aluminum and 5 to 15% vanadium, balance substantially titanium, characterized in undergoing marked age hardening and strengthening on solution treating at about 700 to 800° C. and thereafter aging at about 300 to 500° C.

5. A titanium-base alloy consisting essentially of about: 0.5 to 8% aluminum, 0.5 to 15% of beta-promoting elements, at least one of which is vanadium, the content of beta-promoting elements other than vanadium not exceeding one-half the vanadium content, balance substantially titanium, said alloy being characterized in undergoing marked age hardening and strengthening on solution treating at about 700 to 800° C. and thereafter aging at about 300 to 500° C.

6. A titanium-base alloy consisting essentially of about: 0.5 to 8% aluminum and 0.5 to 15% vanadium, balance substantially titanium, characterized in being age hardenable by solution treating at about 700 to 800° C. and subsequent aging at about 300 to 500° C. to impart in ultimate strength of at least 140,000 p. s. i., a tensile elongation of at least 2% and a minimum bend ductility of not over 20T.

7. The method of age hardening a titanium-base alloy consisting essentially of about: 0.5 to 8% aluminum and 0.5 to 15% vanadium, which consists in soaking at a temperature of about 650 to 800° C. and thereafter aging at about 300 to 600° C.

8. An alloy consisting essentially of about: 0.5 to 8% aluminum, 0.5 to 15% of metal of the group vanadium, columbium and tantalum; chromium up to one-half of the metal of said group present; metal of the group manganese and iron up to one-quarter of the metal of the group vanadium, columbium and tantalum present; metal of the group tungsten, copper, nickel, cobalt, silicon and beryllium up to one-eighth of the metal of said group vanadium, columbium and tantalum present, balance substantially titanium, characterized in having in the annealed condition a minimum bend ductility of not more than 20T, a minimum tensile elongation of about 10%, and a tensile strength at least 30% in excess of the unalloyed titanium base metal.

9. An alloy consisting essentially of about: 0.5 to 8% aluminum, 0.5 to 15% of metal of the group vanadium, columbium and tantalum, balance substantially titanium, characterized in having in the annealed condition a minimum bend ductility of not more than 20T, a minimum tensile elongation of about 10% and a tensile strength at least 30% in excess of the unalloyed titanium base metal.

10. An alloy consisting essentially of about: 0.5 to 8% aluminum, 0.5 to under 10% of metal of the group vanadium, columbium and tantalum; chromium up to one-half the metal of said group present; metal of the group manganese and iron up to one-quarter of the metal of the group vanadium, columbium and tantalum present; metal of the group tungsten, copper, nickel, cobalt, silicon and beryllium up to one-eighth of the metal of the group vanadium, columbium and tantalum present; up to 0.5% carbon, up to a total of 0.2% of oxygen and nitrogen, balance substantially tiitanium, characterized in having a tensile strength at least 30% in excess of the unalloyed titanium base metal, a minimum bend ductility of under 20T and a tensile elongation of at least 5%.

11. An alloy consisting essentially of about: 0.5 to 8% aluminum, 0.5 to under 10% of metal of the group vanadium, columbium and tantalum; up to 0.5% carbon, up to a total of 0.2% of oxygen and nitrogen, balance substantially titanium, characterized in having a tensile strength at least 30% in excess of the unalloyed titanium base metal, a minimum bend ductility of under 20T and a tensile elongation of at least 5%.

12. A titanium base alloy consisting essentially of about: 0.5 to 8% aluminum, 0.5 to 15% vanadium, 0.5 to 5% of at least one element selected from the group consisting of chromium and molybdenum, and the balance substantially titanium, characterized in having in the annealed condition a tensile strength of at least 100,000 p. s. i.

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