DEVELOPMENT OF BETA TITANIUM ALLOYS

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ABSTRACT: In this paper, some beta titanium alloys commonly used in China, Russia and US are classified according to the microstructure of metastable beta phase. The molybdenum equivalence, electron concentration and stability coefficient K_β of beta phase, which were proposed to characterize beta titanium alloys by researchers around the world, are calculated with the common beta titanium alloys, and the development trend is also discovered. The researches and applications of the major beta titanium alloys in China, Russia and US are introduced in detail, and the characteristic of beta titanium alloys and the procedure of their working temperature increase through 300, 370 to 450℃ are also described. It is helpful for the researches and applications of titanium alloys.

KEY WORDS: Beta titanium alloy, Molybdenum equivalence

1. INTRODUCTION

Titanium alloys are microstructurally divided into near alpha, alpha+beta, beta and ordered alloys. This paper is mainly concerned with the development and applications situation of beta titanium alloys in China, Russia and USA.

2. CLASSIFICATION OF BETA TITANIUM ALLOYS

According to the microstructure of metastable beta phase, beta titanium alloys are divided into stable beta, metastable beta, and near beta alloys.

The data of molybdenum equivalence, stability coefficient K_β of beta phase and electron concentration calculated with some beta titanium alloys commonly used in China, Russia and US are given in Table 1. From these data, a trend can be seen that the molybdenum equivalence, K_β and electron concentration of metastable beta titanium alloys are decreasing, which means the decrease in the stability of metastable beta phase. For example, among the metastable beta alloys, Ti-15V-3Cr-3Sn-3Al has the lowest values of molybdenum equivalence, K_β and electron concentration, and the stability of metastable beta phase in this alloy is also the lowest. Among the three categories of beta titanium alloys, near beta alloys have the lowest molybdenum equivalence, the lowest K_β and the lowest electron concentration, and the stability of metastable beta phase in this category is also the lowest. The stability of beta phase in stable beta alloys is the highest and that in metastable beta alloys is in the middle[1].

Table 1 Molybdenum equivalence, K_β and electron concentration of some beta titanium alloys

Category	nominal composition	Molybdenum equivalence	K_β	Electron concentration
stable beta	Ti-32Mo	32	3.2	4.64
metastable beta	Ti-13V-11Cr-3Al	23	2.38	4.32
metastable beta	Ti-7Mo-11Cr-3Al	21.6	2.27	4.33
metastable beta	Ti-5Mo-5V-8Cr-3Al	18.2	1.96	4.28
metastable beta	Ti-8.5Mo-8.5V-1.2Fe-1.2Cr-2Al	17.6	1.85	4.31
metastable beta	Ti-3Al-8V-6Cr-4Mo-2Zr	16	1.76	4.25
metastable beta	Ti-15V-3Cr-3Sn-3Al	12	1.37	4.18
near beta	Ti-10V-2Fe-3Al	9.5	9.5	1.13
near beta	Ti-5Mo-5V-2Cr-3Al	8.6	1.10	4.16
near beta	Ti-5Mo-5V-1Fe-1Cr-5Al	7.9	1.21	4.16

3. THE EVOLUTION OF BETA TITANIUM ALLOYS

3.1 Beta Titanium Alloys in The United States

During the very early days of the titanium industry, Ti-30Mo, Ti-40Mo and Ti-13V-11Cr-3Al (B120VCA) were introduced by Rem-Cruin in the USA. Because of its plate and sheet formability, and subsequent age hardenability, in the 1960's B120VCA became the backbone alloy for the SR-71 "Blackbird" high Mach reconnaissance plane. The entire skin, landing gears, wing beams, fuselage bulkheads and frames were made out of this alloy. Melting segregation caused by high Cr content and sluggish aging response in B120VCA led to the development of the alloys Ti-1Al-8V-5Fe (1-8-5), Ti-8V-8Mo-2Fe-3Al, and Ti-11.5Mo-6Zr-4.5Sn (Beta III), but these three alloys did not get commercialized. Three major alloys Ti-3Al-8V-6Cr-4Mo-4Zr (Beta C), Ti-10V-2Fe-3Al (10-2-3) and Ti-15V-3Cr-3Sn-3Al (15-3), which were introduced between 1969 and 1978, remain in commercial production today. To meet the need of the matrix in metal matrix composite (MMC) with high oxidization resistance, titanium alloy Beta 21S (Ti-15Mo-2.6Nb-3Al-0.2Si) was introduced in the USA. New alloys, such as medical application alloys, fastener alloys and lower cost high strength alloys are now in study. The major beta titanium alloys produced in the USA are given in Table 2[2].

Table 2 Composition, category, applications, source, and year of introduction of major beta titanium alloys in USA, ***listed by the descending order of their Mo Equivalence***

Alloy Composition	Commercial Name	Category (Mo Equivalence)		actual and potential applications	Introduced year – by
Ti-35V-15Cr	Alloy C	beta	(47)	burn resistant alloy	90-P&W
Ti-40Mo		beta	(40)	corrosion resistance	52-RemCru
Ti-30Mo		beta	(30)	corrosion resistance	52-RemCru
Ti-6V-6Mo-5.7Fe-2.7Al	TIMETAL 125	metastable	(24)	high strength aircraft fasteners	90-TIMET
Ti-13V-11Cr-3Al	B120VCA	metastable	(23)	airframe, landing gear, springs	52-RemCru
Ti-1Al-8V-5Fe	1-8-5	metastable	(19)	fasteners	57-RMI
Ti-12Mo-6Zr-2Fe	TMZF	metastable	(18)	orthopedic implants	92-Howmedica
Ti-4.5Fe-6.8Mo-1.5Al	TIMETAL LCB	metastable	(18)	low cost, high strength alloy	90-TIMET
Ti-3Al-8V-6Cr-4Mo-4Zr	Beta-C	metastable	(16)	oil fields, springs, fasteners	69-RMI
Ti-8V-8Mo-2Fe-3Al	8-8-2-3	metastable	(15)	high strength forgings	69-TIMET
Ti-15Mo-2.6Nb-3Al-.2Si	Beta-21S	metastable	(13)	oxidation/corrosion resist., MMC	89-TIMET
Ti-15V-3Cr -3Sn-3Al	15-3	metastable	(12)	sheet, plate, airframe castings	78-USAF
Ti-11.5Mo-6Zr-4.5Sn	Beta III	metastable	(12)	high strength	69-Crucible
Ti-10V-2Fe-3Al	10-2-3	metastable	(9.5)	high strength forgings	71-TIMET
Ti-5Al-2Sn-2Zr-4Mo-4Cr	Ti-17	beta-rich	(5.4)	high strength, medium temp.	68-GEAE

3.2 Beta Titanium Alloys in Russia

Russia paid great attention to the development of beta titanium alloys. In early 1960's, BT15 was introduced, followed by several metastable alloys, i.e. BT30 (Ti-11Mo-6Sn-4Zr), BT32 (Ti-2Al-8.5Mo-8.5V-1.2Fe-1.2Cr), BT35 (Ti-15V-3Cr-3Sn-3Al-1Mo-0.5Nb-0.5Zr) and TC6 (Ti-3Al-7V-10.5Cr-4Mo-0.7Fe), and one near beta titanium alloy BT22 (Ti-5Mo-5V-5Al-1Fe-1Cr).

The major beta titanium alloys in Russia are given in Table 3.

Table 3 Composition, category and applications of major beta titanium alloy in Russia,
listed by the descending order of their Mo Equivalence

Composition	Commercial name	Category (Mo equivalence)		Actual and potential applications
Ti-33Mo	4201	beta	(33)	corrosion resistant alloy
Ti-7V-10.5Cr-4Mo-0.7Fe-3Al	TC6	metastable beta	(24.5)	high strength alloy
Ti-7Mo-11Cr-3Al	BT15	metastable beta	(21.6)	high strength alloy
Ti-8.5Mo-8.5V-1.2Fe-1.2Cr-2Al	BT32	metastable	(17.6)	high strength sheet
Ti-15V-3Cr-3Sn-3Al-1Mo-0.5Nb-0.5Zr	BT35	metastable	(12.3)	high strength airframe castings
Ti-11Mo-6Sn-4Zr	BT30	metastable	(12)	high strength alloy
Ti-5Mo-5V-1Fe-1Cr-5Al	BT22	near beta	(7.9)	high strength forgings

3.3 Beta Titanium Alloys in China

China is rich in titanium source, and the development of titanium industry is significant in China. The research work of titanium alloys started in 1956 in General Research Institute for Non-ferrous Metals (GRINM, Beijing), and two beta titanium alloys Ti-13V-11Cr-3Al and Ti-8Mo-11Cr-3Al were developed. In early 1960's, another alloy Ti-5Mo-5V-8Cr-3Al was introduced. After production test in industry, China's first standard for titanium alloys was made in 1970, which had 21 brands including two beta titanium alloys TB1 (Ti-8Mo-11Cr-3al) and TB2 (Ti-5Mo-5V-8Cr-3Al). Thereafter, several beta titanium alloys such as TB3, TB4, Ti-5523 and Ti-10V-2Fe-3Al were subsequently developed at different institutes. Other four beta titanium alloys in China, which were introduced after 1980's and are in the period of application test, are also given in Table 4.

Table 4 Composition, category and application of major beta titanium alloys in China,
listed by the descending order of their Mo equivalence

Composition	Commercial name	Category (Mo equivalence)		Actual and potential applications
Ti-32Mo		beta	(32)	corrosion resistance alloy
Ti-8Mo-11Cr-3Al	TB1	metastable	(22.6)	high strength alloy
Ti-5Mo-5V-8Cr-3Al	TB2	metastable	(18.2)	satellite-rocket linkage band, fastener, spring
Ti-8V-6Cr-4Mo-4Zr-3Al		metastable	(16)	high strength alloy
Ti-7Mo-10V-2Fe-1Zr-4Al	TB4	metastable	(15.8)	high strength fastener, spring
Ti-10Mo-8V-1Fe-3.5Al	TB3	metastable	(14.8)	high strength fastener, spring
Ti-15Mo-2.7Nb-3Al-0.2Si		metastable	(13)	high strength, medium temperature alloy
Ti-15V-3Cr-3Sn-3Al-1Nb-1Zr		metastable	(12.5)	high strength fastener
Ti-15V-3Cr-3Sn-3Al		metastable	(12)	high strength sheet, fastener
Ti-10V-2Fe-3Al		near beta	(9.5)	high strength forgings
Ti-5Mo-5V-2Cr-3Al		near beta	(8.6)	high strength forgings
Ti-5Mo-5V-1Fe-1Cr-3Al		near beta	(7.9)	high strength forgings
Ti-4Mo-4Cr-2Sn-2Zr-5Al		near beta	(7.4)	high strength, medium temperature alloy

4. THE CHARACTERISTIC OF BETA TITANIUM ALLOYS

4.1 The Characteristic of Stable Beta Titanium alloys

This category of beta titanium alloys retains stable beta structure at room temperature and has high strength and good stability at elevated temperature. These alloys were not developed well due to their high density and difficulty in melting, in spite of their potential applications in thermal resistance alloys. High molybdenum content titanium alloys were introduced because of their good corrosion resistance in different countries.

Beta titanium alloy Ti-35V-15Cr (Alloy C), which was developed by the USA in 1990, has good burn resistance, and its designed working temperature reaches 482℃.

4.2 The Characteristic of Metastable Beta Titanium Alloys

This category of alloys has more than critical concentration of beta stabilizing alloying elements, with Mo equivalence ranging from 12 to 24.5. They have metastable beta structure after solution treatment and water quenching from beta region. These alloys have high strength, high toughness and good hardenability, resulted from the precipitation of alpha phase during the aging of metastable beta structure. In general, these alloys have low stability above 350℃, and they are commonly used below 300℃ with one exception of β 21S alloy, whose working temperature can be improved to 450℃ due to the addition of 0.2wt.% Si in it. Metastable beta titanium alloys can be used at 500℃ for a short period, especially in aerospace. The advantages and disadvantages of beta titanium alloys are given in Table 5.

Table 5 advantages and disadvantages of beta alloys[3]

Advantages	Disadvantages
High strength to density ratio	high density
Low modulus	low modulus
High strength / high toughness	poor low and high temperature properties
High fatigue strength	small processing window (some alloys)
Good deep hardenability	high formulation cost
Low forging temperature	segregation problems
Strip producible, low cost TMP (some alloys)	high springback
Cold formable (some alloys)	microstructrual instabilities
Easy to heat treat	poor corrosion resistance (some alloys)
Excellent corrosion resistance (some alloys)	interstitial pick up
Excellent combustion resistance (some alloys)	

In addition, metastable beta titanium alloys are deeply hardenable in nature. They have higher fracture toughness than α + β titanium alloys at high strength level, and they are suitable for aircraft forgings. However, there are two disadvantages of metastable beta titanium alloys for large area forgings, i.e. low elongation after aging and low modulus. As a result, new near beta titanium alloys with high strength, high toughness and good hardenabiliby were developed in the USA, Russia and China, in order to meet the need of large area forgings.

4.3 The Characteristic of Near Beta Titanium alloys

This category of alloys has about the critical concentration of beta stabilizing alloying elements, with Mo equivalence ranging from 7.4 to 9.5. The metastable beta in these alloys has low stability after solution treatment and water quenching. There exists two yielding points in the stress-strain curves of these alloys. The first yielding point is caused by the martensitic transformation induced by stress. This category of alloys has a combination of the properties of α + β and metastable β alloys. They have good cold formability in solution state and good combination of high strength, high plasticity and fracture toughness in aging state. They also have excellent thermal formability with much lower formable temperature and forming force than most industrial titanium alloys. In addition, these alloys are suitable for large area forgings due to their good hardenability. One example of these alloys is Ti-17, developed by the USA with a low Mo equivalence of 7.4 and designed working temperature of 372℃.

5. APPLICATIONS OF BETA TITANIUM ALLOYS

5.1 Semi-manufactures of Beta Titanium Alloys

Beta titanium alloys have good machinability. They are suitable for being made into sheet, ribbon, foil, bar, wire, forging, die forging, casting, section, and other semi-manufactures to meet the needs of applications in various areas.

5.2 Applications of Beta Titanium Alloys

Beta titanium alloys were firstly used in aerospace and aeronautics field, then extended to oil and chemical industries.

5.2.1 Airframe Applications

Many airframe applications were reviewed in detail by Boyer[4].

Airframe applications were the first major use of beta titanium alloys. The use of Ti-13V-11Cr-3Al (B120VCA) on the SR-71 "Blackbird" launched the era of beta alloys in the mid 60's, and until today represents the most extensive use of titanium in any aircraft. The product form used included sheets, extrusions, billets, bars, and forgings for producing the entire skin, the complete main and nose landing gears, bulkheads, longerons, ribs, and rivets. In the mid 80's almost 100 aft nacelle structure parts on each B1-B bomber, and engine access doors on the Fairchild-saab FS-340 commuter plane were made out of 15-3.

The first beta alloy forgings used on a commercial aircraft were few Ti-10-2-3 replacements for 15-5PH steel parts on the Boeing 757. More forgings were used on the McDonnell Douglas C-17 military cargo plane. However, only the upcoming Boeing 777, will use 10-2-3 extensively. The most significant use will be in the main landing gear structure, which includes 343mm diameter×3m long truck beam and most other beams, as a replacement to 4340M steel, for a total weight saving of 270kg. Other major high strength 10-2-3 parts, like the 1.6m long flap tracks, the nose gear steering mechanism and many other smalleer parts may make the use of this alloy more extensive than the Ti-6-4 on the 777[4]. The Russians also have made an extensive use of high strength BT22 forgings in the main landing gear, spars, beams, longerons, stingers, fasteners, and springs on the IL-86, and IL-96-300.

The high strength BT35 alloy castings have been used extensively in Russian airframes. High strength beta alloy castings, 15-3, will be used for the first time in the USA on the 777.

Beta alloy springs have been used extensively on military and civilian planes. The low modulus, high strength, and low weight make beta alloys an ideal material for aerospace spring products. The first use of Ti-13-11-3 (B120VCA) springs was by McDonnell Douglas in the mid 70's on the DC-9 and DC-10. In the mid 80's, Beta C springs were developed as a replacement, and are used on all Boeing, McConnell Douglas, and Lockheed airframes. Beta-C springs will be used on the Airbus A-330, and A-340 [4].

The use of Ti-15V-3Cr-3Sn-3Al alloy as a replacement of 30CrMnSiA in the production of the beam of deceleration parachute cabin and the fuselage bulkhead can reduce weight 40% and 26.1%, respectively[5].

5.2.2 Applications in Aerospace

TB2 alloy ribbon is still being used to make satellite-rocket linkage band since its first use in 1984. Furthermore, the shell of solid fuel rocket engine can be produced through the combination weldment of TB2 plates and forgings. TB2 alloy foil can also be used to make dimpled shield and multi-layer thermal resistant tile. Ti-5523 alloy forgings can be made into satellite retrieving device and its bars can be made into connecting rod of satellite-rocket linkage band. TB3 can be made into high strength fasteners, various springs, spring ribbon and high hardness cutting tools.

5.2.3 Application in Other Fields

TB2 alloy bars have been used to make drill rod, and TB2 forgings are used into biological centrifugal machine.

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