Development and Application of Titanium Alloy Aerospace Fasteners

by Wen-Hai Liu

I. Preface

The research of titanium alloy originated from aerospace and the development of aerospace industry also promoted the development of titanium alloy. Titanium alloy has the advantages of high strength, light weight, corrosion resistance, high temperature resistance, combustion resistance, non-magnetic property and so on, and its service temperatureis 150-200℃ higher than that of aluminum alloy. Therefore, titanium alloy will be a better choice for the parts of aircraft structure where aluminum alloy fasteners cannot be used due to high working temperature. Additionally, due to its good compatibility with composite materials, the demand for titanium alloy fasteners is growing with the increasing amount of titanium alloy and composite materials used in advanced military and civil aircrafts, which has basically replaced alloy steel fasteners in the military and civil aircrafts of the United States.

II. Types and Characteristics of Titanium Alloy Aerospace Fasteners

Titanium alloy fasteners for aerospace mainly include rivets, bolts and special fasteners, among which titanium alloy bolts are the broadest used. Titanium alloy bolts can be divided into ordinary titanium bolts, high lock bolts, Eddie bolts and interference bolts. Ordinary titanium bolts are classified with countersunk-head bolt, hexagon bolt, twelve-point bolt, twelve-point flange according to head type. High Lock Bolt is a kind of threaded fastener that can be installed on one side, which is one of the fasteners widely applied on aircrafts and can be divided into tensile type and shear type according to stress condition. Eddie Bolt (**Fig. 1**) is the fourth generation of the nut system, whose load can be controlled to prevent the parts from damaging, so it is suitable to connect composite materials. Interference Bolt is a one which can improve the fatigue life of structure by using interference fit connection. In civil aircrafts, almost all the non-detachable torsional shear fasteners utilize the interference fit.

Fig. 1 Appearance of Eddie Bolt Data source: https://www.howmet.com

Under the same strength index, the weight of a titanium alloy fastener is 70% lighter than that of a steel one and its electrode potential is similar to that of carbon fiber composite material, so titanium alloy becomes the only connection material of composites. Also, titanium has low elastic coefficient (about 100GPa), high yield strength, large elastic strain, and no magnetism, which is very important in preventing the loosening of fastened bolts and the interference of magnetic field. Furthermore, titanium alloy has high corrosion resistance under various climatic conditions, and its fatigue strength and stress concentration sensitivity are better than those of similar steel, which is critically why titanium alloy is widely used for manufacturing aerospace fasteners.

III. Types and Characteristics of Titanium Alloy

Fig. 2 is a pseudo binary phase diagram of titanium alloy. Titanium alloy can be distinguished by the addition of β-stable elements to the category and phase composition. When the content is low, it is α-type/near α type; when the content level is high, it is β type; and when the content level is half high, it is α-β type. Moreover, β type can be subdivided into metastable type and stable type, the Mo equivalent of the former is controlled between 10~25 and that of the latter is>25.

1. α type/nearα type:

α phase (or α phase with additional trace intermetallic compound) annealed in hexagonal close-packed (HCP) has a higher work hardening rate, poor formability, and cannot be strengthened by heat treatment, so its strength is inferior to the other two types. α-type alloy has good creep resistance and weldability, which is the first choice for the conditions of high temperature and corrosion resistance, and also suitable for low temperature environment since

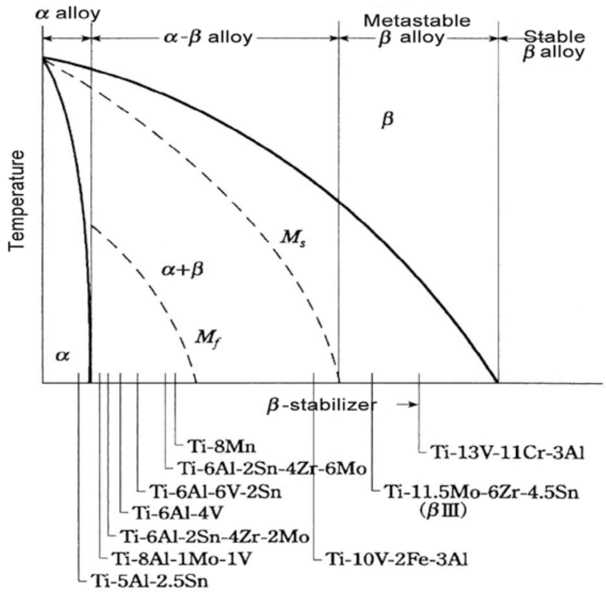

Fig. 2 Pseudo Binary Phase Diagram of Titanium Alloy

Data source: Light metals, Vol. 65, No. 9 (2015)

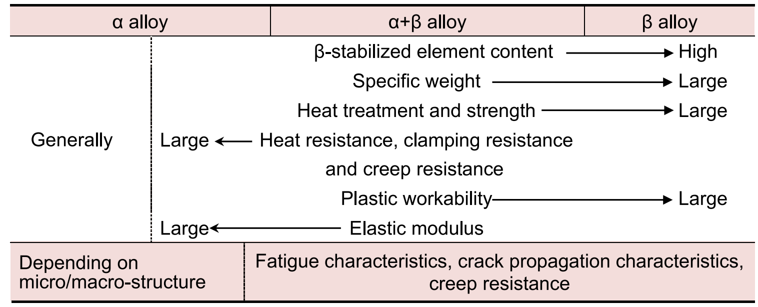

Fig. 3 Tendency of Titanium Alloy Material Properties

Data source: Special steel, July 2019

it has no cold brittleness, such as pure titanium, Ti-3Al-2.5V. Forging defects are easy to happen in α-type alloy due to its poor forging property, which can be controlled by reducing the processing rate per pass and frequent heat treatment. The room temperature strength of near α alloy is higher than that of α-type alloy, and its creep strength is higher than that of other titanium alloys.

2. α-β type:

α+β phase in annealed structure has better room temperature strength and plasticity than that of α-type titanium alloy and its corrosion resistance is also good, but the weldability and heat resistance are poorer than that of α-type titanium alloy. It has good hot workability but is difficult for cold forming. It can be strengthened by heat treatment and has high creep strength as well as high temperature tensile strength. The highest service temperature can be up to 500℃ and it is the titanium alloy with the most far-ranging application, such as Ti-6Al-4V, Ti-6Al-2Sn-4Zr-6Mo.

3. β type:

Single-phase β solid solution in annealed or quenched state of body-centered cubic (BCC) has the best formability among the three kinds of alloys, and a few have excellent corrosion resistance. The commonly used heat treatment method is the solid solution treatment and then aging at 450~650℃, the β base will precipitate out the small α secondary phase, which is the strengthening mechanism of the β alloy. Since the β titanium alloy precipitates more α phase in aging than other kinds of titanium alloys, and contains more of α-β phase interface to obstruct the dislocation motion, the room temperature strength of β titanium alloy is the highest, with the most excellent fracture toughness, but its quenching structure is not stable, and the heat resistance is not high, so the operating temperature is usually below 200℃, the representative alloys include Ti-10V-2Fe-3Al, Ti-15V-3Cr-3Al-3Sn, Ti-3Al-8V-6Cr-4Mo-4Zr, and Ti-35V-15Cr, etc.

The crystal structure of each type of titanium alloy is formed by two phases, namely α phase and β phase. The number, size and morphology of each phase are different, which greatly affects the malleability and mechanical properties. The more β-stable elements (such as Mo, V, Cr, Fe, etc.) are, the more β phase is, which usually has better malleability (cold workability). On the other hand, if the amount of β stable elements is too much, the transformation points of β phase (transition temperature between α+β two-phase region and single-phase β) will decrease. Thus, when forging in the two-phase region, the deformation resistance of α-β type alloy will increase and more forging pressure is needed. Therefore, it is necessary to select the appropriate combination of alloy and forging method according to the application situation and required characteristics. The tendency of titanium alloy material properties is shown in **Fig. 3**, and the mechanical properties comparison of representative titanium alloys is shown in **Table 1.**

Among various types of titanium materials, α-type and α-β type are well applied in diversified industries. Although β-titanium alloy has been developed as early as 1950's, it is only used for national defense and aerospace military in most countries due to high cost and difficult melting, so its characteristics are less known than α-type and α-β type. However, it has gradually been used in the civil aviation, biomedical, industrial, livelihood and sports goods market and attracted much attention in recent years due to its excellent properties.

Alloy type	Composition	Heat treatment	Mechanical properties		
			Tensile strength -MPa	Yield strength -MPa	Elongation -%
α alloy	Ti-5A1-2.5Sn	Annealing	860	800	16
α+β alloy	Ti-8A1-1Mo-1V	Annealing	1,000	950	15
	Ti-6A1-2Sn-4Zr-2Mo	Annealing	980	890	15
	Ti-3Al-2.5V	Annealing	680	590	20
	Ti-6Al-4V	Annealing	980	920	14
	Ti-6Al-2Sn-4Zr-6Mo	Aging	1,270	1,180	10
β alloy	Ti-13V-11Cr-3Al	Aging	1,270	1,230	8
	Ti-3Al-8V-6Cr-4Mo-4Zr	Aging	1,440	1,370	7
	Ti-15Mo-5Zr3Al	Aging	1,470	1,450	14
	Ti-15V-3Cr-3Sn-3Al	Aging	1,230	1,110	10

Table 1. Mechanical Properties Comparison of Representative Titanium Alloys

Data source: Special steel, July 2019

IV. Titanium Alloy Materials for Rivet Fasteners

The most important thing for rivets is the cold workability of materials, only those made of materials with good cold plasticity can be installed through cold riveting. Titanium alloy rivets are usually used in the parts with low strength but high corrosion resistance requirements. β-type titanium alloy has excellent cold working performance due to its single β phase in solid solution state and its atomic structure of body-centered cubic, which is the best material for titanium alloy rivets.

1. Ti-5Mo-5V-8Cr-3Al (Chinese Grade TB2)

TB2 is a kind of metastable titanium alloy, which has excellent cold formability and weldability under solution treatment and is suitable for all kinds of cold rivets and sometimes for small-size bolts. Its service temperature is generally below 300℃ and the space fastener can work up to 500℃ in a short time.

2. Ti-15V-3Cr-3Sn-3Al (Chinese Grade TB5)

TB5 is a kind of metastable β-type titanium alloy, which was initially mass produced by American TIMET Company. It can be used for cold forming of various complex parts (such as riveting) in solution state since its cold forming ability is equivalent to that of pure titanium, and its tensile strength at room temperature can reach more than 1000MPa after aging. Because of high content of V element and poor high temperature oxidation resistance, it is generally used in the working environment below 200℃, but this alloy has excellent corrosion resistance.

3. Ti-45Nb alloy

Ti-45Nb alloy is a special material for rivets, with outstanding advantages of high plasticity (elongation up to 20%, reduction of area up to 60%-80%) and excellent cold working performance. Its shear strength (≥350Mpa) and tensile strength (≥450MPa) are higher than that of pure titanium, and its cold deformation resistance is lower than that of pure titanium, so it is very suitable to be used as rivets for composite materials connection. This alloy was listed in AMS 4982 specification in 1974 and revised to AMS 4982C in 2002, which has completely replaced pure titanium in aerospace rivet products in the United States. The bimetallic rivets made of Ti-45Nb alloy and Ti-6Al-4V alloy have been comprehensively used in Airbus and Boeing aircrafts.

For rivets with the requirements of high shear strength and no deformation of rivet rod during installation, bimetallic titanium alloys are generally used. It is composed of Ti-6Al-4V rivet rod and Ti-45Nb head, which are closely fused to form an integral solid core rivet after inertial friction compression. When riveting with this kind of bimetallic rivet, just a small impact force can produce plastic deformation on the Ti-45Nb rivet head, while the Ti-6A1-4V rivet rod does not deform. Bimetallic titanium alloy rivets are widely used in the riveting of titanium alloy components and composite components in aircrafts such as B-1 bombers and Boeing. For example, 4,000 bimetallic rivets are used in the leading edge of the F-14 warcraft in the United States, of which the fatigue performance is equivalent to that of a high lock bolt, but the cost can be reduced by 50% and the weight can be decreased by 30% - 40%. The cost of this bimetallic rivet is lower than that of other β-type titanium alloy rivets.

V. Titanium Alloy Materials for Bolt Fasteners

The titanium alloy material used for bolts is generally required for high tensile strength and shear strength after heat treatment, and its strength level shall be equivalent to ASTM 4340 (Chinese Grade 30CrMnSiA) high strength medium carbon quenched and tempered alloy steel commonly used in aircraft structures.

1. Ti-6Al-4V (Tensile strength ≥ Grade 1100MPa)

Ti-6Al-4V titanium alloy (ASTM Gr.5, Chinese Grade TC4) was first developed by the United States in 1954, which has become an international titanium alloy with widespread application in aerospace, people’s livelihood and other industries. It has extensive application in the manufacture of beams, frames, landing gears, fasteners, engine fans, compressor disks, casings, blades of aircrafts and accounts for more than half of the production of titanium alloy at present. This alloy has good formability and super-plasticity, its α-β/β transition temperature is 980-1,010℃ and the long-term working temperature can be up to 350-400℃. However, this alloy cannot be cold formed since it is α-β dual phase alloy, the nail head must be hot forged and the heat treatment needs vacuum water quenching and aging, which requires high on processing equipment and technology. The disadvantages of hot forging are as follows: local burn, overheating and surface oxidation are prone to occur when the blank is heated, automatically continuous manufacturing is difficult and the production efficiency is low.

2. Ti-3Al-5Mo-4.5V(Former Soviet Union Grade BT16) (Chinese Imitation Grade TC16)

As a special cold forging titanium alloy for fasteners developed by the former Soviet Union, BT16 is a kind of martensite α+β dual phase titanium alloy with β stability coefficient of 0.83, which is close to the critical composition. This alloy is mainly used to make aerospace fasteners with working temperature below 350℃ and its α-β/β transition temperature is 860±20℃. Smaller β grains and volume ratio of β phase up to 25% in annealed state determine that BT16 has excellent room temperature processing plasticity, so the cold forming of fastener heads can be completed at room temperature, which significantly improves the bolt production efficiency and reduces the production cost. After solution aging heat treatment, its strength can reach 1,030~1,180MPa. The titanium alloy bolts fasteners of former Soviet Union are mainly made of BT16, which has been used for decades without any quality accident.

3. Ti-10Mo-8V-1Fe-3.5Al (Chinese Grade TB3)

TB3 is also a kind of metastable β-type titanium alloy that can be directly cold forged and heat treated, which has the advantages of excellent cold formability in solution treatment state. The cold forging ratio (Dt/Do) can reach 2.8 and high strength can be obtained after solution and aging treatment. It is mainly used for 1,100MPa high strength aerospace bolts with service temperature lower than 300℃ and is used as the material of rivets.

4. Ti-6Al-2.5Mo-1.5Cr-0.5Fe-0.3Si (Russian Grade BT3-1) (Chinese Imitation Grade TC6)

Bt3-1 is a titanium alloy fastener material developed by Russia, which can withstand high temperature below 500℃ and has been widespread in this country. Compared with TC4 titanium alloy, it is more sensitive to temperature and the manufacturing of fasteners is more difficult. As a kind of martensite α+β dual phase titanium alloy with good comprehensive properties, it is usually used in annealed condition and can be strengthened by proper heat treatment. This alloy has excellent oxidation resistance and corrosion resistance, the parts made of it can work at 400℃ for more than 6,000 hours and 450℃ for more than 2,000 hours. After isothermal annealing, the room temperature tensile strength is higher than 980MPa, the yield strength is higher than 840MPa, the elongation is more than 10%, and the reduction of area is more than 25%. The tensile strength at 400℃ is higher than 720MPa, the elongation is more than 14%, and the reduction of area is more than 40%. Furthermore, solution and aging treatment can also be performed to further improve its service strength.

Fig. 4 1280MPa Grade TB8 Titanium Alloy Bolt

Data source: Aviation manufacturing technology, issue 16, 2013

5. Ti-3Al-2.7Nb-15Mo (β21S)

β21S is a metastable βtype titanium alloy developed by TIMET Company for NASP project in 1989, with tensile strength higher than 1280MPa. It has excellent cold and hot working performance, deep hardenability, good creep resistance, strong oxidation and corrosion resistance. This alloy was first listed in the ASTM standard of the United States in 1994 and is mainly used in the manufacture of space shuttle titanium composite materials and aircraft engine pod parts such as Boeing 777. Because the β stable elements used in the alloy are molybdenum and niobium with high melting point and oxidation resistance, instead of vanadium with poor oxidation resistance used in TB2 and TB3 titanium alloys, the long-term service temperature of fasteners made of this alloy can reach 550°C, which completely solves the problem of low service temperature (no more than 300°C) of traditional high-strength β titanium alloy fasteners. The Chinese Imitation Grade of this alloy is TB8, and the appearance of the titanium alloy bolt thereof is shown in **Fig. 4**.

The future development trend of aerospace technology requires high specific strength of new fasteners, that is, light weight and high strength. Therefore, the United States, Russia, France and other aerospace powers are actively developing high-strength titanium alloy materials and fasteners with tensile strength above 1200Mpa. In recent years, Alcoa has developed Timetal 5553 (Ti-5A1-5Mo-5V-3Cr r) titanium alloy high-strength bolts, of which the tensile strength is over 1300MPa, the shear strength is greater than 745MPa, and the elongation is more than 10% after solution and aging. All performance indicators fully meet the requirements of the typical 1250MPa cadmium plated alloy steel fastener specification. SPS Aeronautical Fastener Group adopts Aerlite180 bolts made of SPS TITANTM761 titanium alloy with tensile strength and shear strength over 1240MPa and 745MPa respectively, which can reach the strength level of many alloy steel and corrosion-resistant alloy fasteners, and reduce the weight by 40%.

VI. Conclusion

At present, more than 70% of titanium alloy fasteners used in aerospace are still made of Ti-6Al-4V because of its low density, good fatigue resistance and simple composition. Although the cold forging cost of β titanium alloy is low, it has disadvantage of high density; its fatigue resistance is not as good as that of Ti-6Al-4V even though its strength is equivalent to that of Ti-6Al-4V, meanwhile its composition is complex and the cost of semi-finished products is high. Due to the same need for vacuum aging treatment, the cost of a finished fastener is still higher. With the increasing requirements of global aerospace industry for aircraft performance, the future high-performance titanium alloy aerospace fasteners set the requirements for higher strength, higher fracture toughness, higher fatigue and good cold working performance of the materials concerned. ■

Holes To Fasten Things With

by Peter Standring

Holes cost money! OK, so the statement doesn't have the impact of, E = MC2 but non-the-less it is a fundamental truth. Try to buy one, make one or create one and it can become both expensive and confusing.

Two stories on this problem come to mind, one read about, the other shown. Many people travelling the iconic Route 66 through Winslow, Arizona will have passed by Meteor Crater. Formed around 50 000 years ago by an asteroid, it found media fame when NASA used it to train its Moon bound astronauts. Before that, a Philadelphia Lawyer spent much of his summers and most of his money digging holes in the bottom seeking the meteorite which did the damage. When he died, virtually bankrupt with nothing to show for his efforts, his wife wrote to the Governor of Arizona asking if he would like to buy the hole. He politely refused her invitation by saying he already had a bigger one, the Grand Canyon.

On a much smaller scale, a friend of mine who had a business refurbishing large forging presses etc., invested half a million British Pounds in constructing a deep pit within his factory. On completion, he was very concerned to find his local taxman refused to allow his investment as Capital Expenditure. Inviting the official to view his pit, my friend was intensely frustrated to find that to the taxman, his hole