Influence of heat treatment on the microstructure and mechanical properties of TC17 Titanium Alloy

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Abstract. The influence of heat treatment on the microstructure and mechanical properties of TC17 titanium alloy was investigated by changing holding time before forging and aging temperature after β-forging. A better heat treatment mechanism was chosen according to its working requirements. The results showed that the holding time and aging temperature had a significant influence on microstructures and mechanical properties of TC17 alloy. With the increase of holding time before forging in the single β phase region, the original β grain size enlarge, the strength and fracture toughness decrease, and the plasticity increases. The size of lamellar α-phase bundles enlarge with the rise of aging temperature after β-forging, the orientated relationship becomes simple, and the content of β-transformation increases. And the plasticity and fracture toughness of the alloy increase, the strength and hardness decreases. The fracture toughness is better under the heat treatment mechanism at 873℃/2h +918℃/64min before forging, 800℃/4h,WC+660℃ /8h AC after forging, with the high and low cycle fatigue properties meet the technical requirements.

Key Words: Heat treatment, Forging, Microstructure

1. Introduction

Titanium alloys have been widely used in aircraft, aircraft engines and other fields owing to their high strength and toughness, relatively low density, excellent creep and corrosion resistance[1-2]. TC17 (Ti-5Al-2Sn-2Zr-4Mo-4Cr) of near β-titanium alloy belongs to medium temperature and high strength titanium alloy. The properties of TC17 correspond with Ti-6A1-6V-2Sn, the abilities of plasticity and fracture toughness are better than Ti-6A1-6V-2Sn and the creep property is higher than Ti-6A1-4V. TC17 alloy has been attracted considerable attention in the fabrication of high load-bearing components, such as fan plate of aircraft engine and compressor disk. TC17 alloy includes α stable element Al and isomorphous β element Mo and eutectic β element Cr、Fe and Si. The tensile strength and yield strength can be enhanced by strengthening α and β phases [3].

It is difficult for titanium alloys to obtain stable and consistent workpiece in production, and it is easy to produce various macroscopic and microcosmic defects, which will affect the mechanical properties of the workpieces. The fracture toughness decreases with the increase of strength of high strength titanium alloy, and the strengthening of alloy properties is constrained by both plasticity and toughness at a certain strength level. Along with the application of damage tolerance design idea in titanium alloy, the fracture toughness of titanium alloy has been attracted more and more attention and research. The fine lamellar structure can be obtained by using β forging, which can improve the fracture toughness of the alloy greatly [4-5]. Titanium alloy β forging has a series of advantages, such as good plasticity, low deformation resistance, high production efficiency and long service life of the forging equipment [6]. TC17 titanium alloy is taken as the research subject in this paper, studying the effect of heat treatment on the microstructure and mechanical properties of TC17 titanium alloy by changing holding time before forging and aging temperature after β-forging, and optimal heat treatment system has been selected according to the service requirements of TC17 titanium alloy, which provides experimental and theoretical basis for actual practice.

2. Materials and procedures

The material used in this investigation was a TC17 forging bar provided by a factory, 250mm in diameter. The measured chemical compositions(wt%) of the bar are as follows: 5.53%Al, 2.23%Sn, 2.29%Zr, 4.30%Mo, 4.08%Cr, 0.12%Fe, 0.01%C, Ti balance. The β transus temperature is 893℃ as determined with the metallographic observation method, as follows: test samples of TC17 titanium alloy were heated at a series of temperatures with 5°C intervals between tests around the expected β transus temperature for 30 min and then water cooling(WC); the β transus temperature is taken about a middle temperature between the temperatures on the basis of the appearance and disappearance of α_p grains. Figure 1 shows the original microstructure of the bar before forging. It could be observed that the original microstructure is typical equiaxed structure, which consists of equiaxed α phase and β transformation structure; The equiaxed α phase is uniformly distributed in the β matrix and contains a small amount of short rod-like α phase.

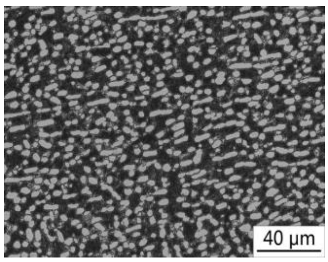

Fig.1 The initial microstructure of TC17 alloy bar

The pre-heating time of titanium alloy billet is calculated by the formula "0.8min/mm×minimum section size(mm)". With reference to the actual production, three heating specification were selected: 873℃/2h+918℃/15min （ specification 1 ）、873℃/2h+918℃/64min （ specification 2 ）、918℃/120min（specification 3）. Isothermal forging of TC17 titanium alloy specimens in β region were carried on the 630t strain rate controllable oil press. The forging temperature and deformation degree are the same and the strain rate is different according to the specimen size, air cooling(AC) after forging. The solid solution temperature after forging was 800℃ and three kinds of different aging temperatures were employed: 620℃, 640℃, 660℃.The specific heat treatment scheme as shown in Table1. The specimens were heat treated in a SX2-10-13 chamber electric furnace; microstructure was observed by Leica DMI3000M metallographic microscope; the room temperature tensile test were conducted using the ENST-1196 stretcher; the fracture toughness (T-L) values were obtained using the INSTRON-1251 model test machine. The properties of high and low cycle fatigue were carried out on the MTS810 electro-hydraulic servo fatigue testing machine.

Tab.1 Subsequent heat-treatment processes after forging

Heat treatment	Heat treatment system
I	800℃/4h，WC+620℃/8h，AC
II	800℃/4h，WC+640℃/8h，AC
III	800℃/4h，WC+660℃/8h，AC

3. Results and discussion

3.1The effect of holding time before forging on microstructure

The microstructure of the TC17 titanium alloy heated by different heating specifications and carried out isothermal forging are presented in Fig2. The parameters of forging are: temperature is 918 ℃，deformation degree is 60%, strain rate is $7.63 \times 10^{-3}s^{-1}$，slow cooling after forging and heat treatment by system II. Under different heating specifications，the microstructure of TC17 titanium alloy after isothermal forging is typical basket-weave structure. The primary equiaxed α phase disappears completely; the precipitated lamellar α phase in β grain boundary is broken remarkably; lamellar and secondary α phase interwoven distribution in intracrystalline, the ratio of length to width is 10 to 1. The original β grain is elongated along the deformation orientation and the ratio of length to width is 2 to 1, a small amount of fine recrystallized grain appears in grain boundary. Under the three heating specifications, the growth degree of the β grain is different due to different holding time at 918℃. The holding time increases gradually from specification I to specification III, and the initial grain size in microstructure increases gradually, but specification III changed little compared to specification II. Owing to the size of the original β grain is large, so the deformation of grain is inhomogeneous in the forging process. As a result, the number of recrystal grains formed nearby the grain boundaries differ greatly. In addition, after the billet was heated at 918℃/2h, forging and heat treatment, more secondary α phases appeared in the β intragranular of the alloy, which precipitated directly from the grain boundaries and grew in the crystal. The lamellar α phase is longer in the crystal, this phenomenon may be on account of the interruption of heating for a certain period during the forging process and the decrease of the die temperature，the deformation degree of the billet increases in the two phase zone.

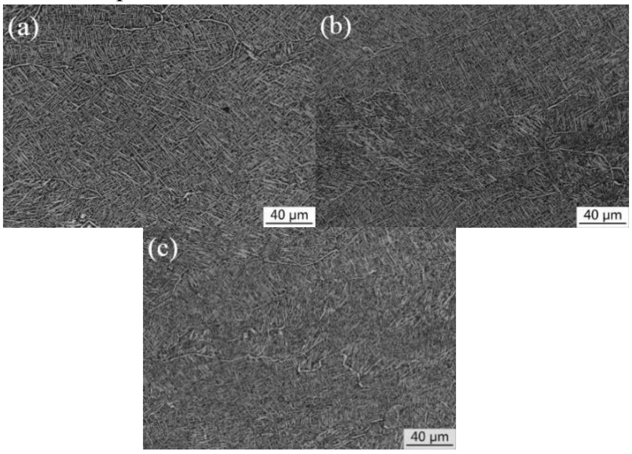

Fig.2 Microstructure of TC17 alloy under different heating specifications（$7.63\times10^{-3}s^{-1}$）

（a）918℃/15min；(b) 873℃/2h+918℃/64min；

(c) 918℃/2h

The microstructure of the TC17 titanium alloy heated by different heating specifications and carried out isothermal forging are presented in Fig3. The parameters of forging are: temperature is 918 ℃，deformation degree is 60%, strain rate is $3.05 \times 10^{-3}s^{-1}$，slow cooling after forging and heat treatment by system II. Under different heating specifications, the microstructure of TC17titanium alloy after isothermal forging is typical basket-weave structure. The lamellar α phase breaks obviously at the grain boundary, lamellar and secondary α phase interwoven distribution in intracrystalline, the ratio of length to width is 10 to 1. The original β grain is elongated along the deformation orientation and the ratio of length to width is 2 to 1, a small amount of fine recrystallized grain appears in grain boundary. The holding time of billets in the β single phase field increases from specification I to specification II, the original β grain size increases, and the number of recrystallized grain decreases near the grain boundary. It could be that the larger grain boundary area and more deformation storage energy of the billet under the heating condition of 918℃ /15min, and it is easier to satisfy the energy condition of recrystallization. Compared with Fig.2，the strain rate decreases and the deformation time increases, the grain size of the recrystallized grains enlargement. In addition, the primitive β grains have more time to coordinate deformation, and the grain deformation inhomogeneity reduces.

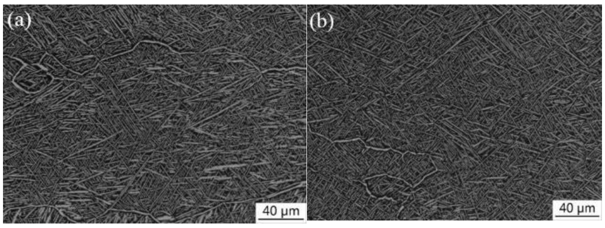

Fig.3 Microstructure of TC17 alloy under different heating specifications（$3.05 \times 10^{-3}s^{-1}$）
（a）918℃/15min；(b) 873℃/2h+918℃/64min；

3.2 The effect of holding time before forging on mechanical properties

The tensile properties at room temperature of the TC17 titanium alloy heated by different heating specifications and carried out isothermal forging are presented in Tab.2 The parameters of forging are: temperature is 918℃，deformation degree is 60%, strain rate is 7.63×10^{-3}s-1，slow cooling after forging and heat treatment by system II.

It is found from the data in table 2 that only the yield strength of specification I exceeds the technical standard, and the other properties of the alloy satisfy the technical requirements. The change of heating scheme will have obvious influence on the properties of TC17 titanium alloy. From specification I to specification III, the heat holding time in β single phase filed increases gradually, the strength of the alloy decreases and the plasticity increases gradually.

The fracture toughness at room temperature of the TC17 titanium alloy heated by different heating specifications and carried out isothermal forging are presented in Table3. The parameters of forging are: temperature is 918℃，deformation degree is 60%, strain rate is 3.05×10^{-3}s-1，slow cooling after forging and heat treatment by system II. The fracture toughness of the alloy after specification I is slightly higher than that of others, the test results of heating specifications II and III are basically same. The fracture toughness of the alloy under the three specifications all reach the technical standard. The fracture toughness of TC17 titanium alloy decreases with the increase of the holding time in β single phase filed, which may be due to the size of the primitive β grains enlarge, the grain boundary area decreases, the grain boundary of the crack propagation path decreases and the energy consumption decreases correspondingly. So the fracture toughness decreases slightly.

Table 2 The room-temperature tensile properties of TC17 alloy at different heating modes

specification	Tensile strength σ_b/MPa		Yield strength $\sigma_{0.2}$/MPa		Elongation δ/%		Area reduction Ψ/%	
	Test	average	Test	average	Test	average	Test	average
1	1302	1299	1242	1238	11.0	10.25	15	16
	1296		1234		9.5		17	
2	1219	1217.5	1168	1168	12.0	12.0	23	20
	1216		1168		12.0		17	
3	1188	1184.5	1136	1134	12.0	13.0	20	21
	1181		1132		14.0		22	
technical standard	≥1120		1020~1193		≥5		≥10	

Table 3 The fracture toughness of TC17 alloy at different heating modes

specification	K_{IC}/ MPa·$m^{1/2}$
1	64.9
2	62.7
3	62.6
technical standard	≥55

3.3 The effect of heat treatment after forging on microstructure

The microstructure of TC17 titanium alloy carried out isothermal forging are presented in Fig4. The parameters of β-forging temperature is 918 ℃ , deformation degree is 60%, strain rate is $7.63 \times 10^{-3}s^{-1}$, and heat treatment by different system. The microstructure of all specimens are: typically basket-weave structure. The primary β grains are elongated and deformed along the direction of metal flow obviously, secondary lamellar α distributes in the β matrix. When the plastic deformation occurs, the grain boundary of α phase is fragmented obviously, and there are more fine recrystallized β grains at the grain boundaries. The stacking fault energy of the β phase of BCC structure is high, the intracrystalline dislocation reduces easily at high temperature, the piling-up of dislocation degree of the grain boundary is relatively larger, the distortion storage required for the recrystallization are easy to satisfy. Furthermore, the dislocation density of crystal boundary is large, so it is easy to occur recrystallization. Therefore, recrystallization grains are formed easily near the grain boundaries during the heat treatment. The near β titanium alloy after solid solution and quench, ω phase and metastable β phase are formed easily in the structure owing to the fast cooling, which is unstable in thermodynamics and will resolve if heated. The subsequent aging process causes the ω phase and metastable β phase transforms into diffuse lamellar α phase[7]. The microstructure, as shown in Fig.4, illustrates that with the increase of aging temperature, the concentration size of secondary α phase in the intracrystalline tend to increase, the distribute orientation became simple, the content of β transus increased.

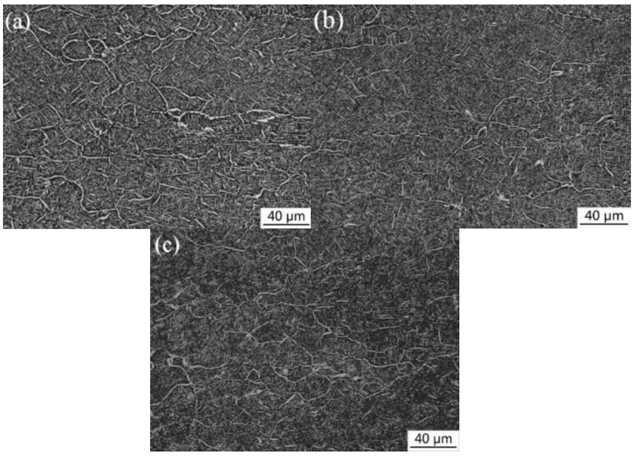

Fig.4 The microstructure of TC17 alloy at different heat-treatments($7.63\times10^{-3}s^{-1}$)
(a) 800℃/4h，WC+620℃/8h，AC；(b) 800℃/4hWC+640℃/8h，AC；(c) 800℃/4h，WC+660℃/8h，AC

When the strain rate decreased to $3.05\times10^{-3}s^{-1}$, other parameters of β-forging are same, the microstructure of specimens shows in Fig.5. The microstructure of all specimens are typically basket-weave structure, the primary β grains are elongated along the direction of specimen deform and the ratio of length to width is more than 2:1. The secondary α phase precipitate and intertwine distribute in the crystal, the grain boundary α phase is broken obviously, as the strain rate decreases, the forging time increases from 122s to 305s, and the distortion energy produced by deformation could has more time to release through recovery. In addition, the density of pile-up in the grain boundary decreases, the condition of recrystallization nucleation cannot be fully satisfied, so the number of recrystallized grains decreases. After solid solution, the alloy precipitated ω phase and metastable β phase, which will transform into secondary α phase during the subsequent aging process. Fig.5 verifies the results that with the increasing of aging temperature, the distribution of the secondary α phase in the crystal tended to be simple, and the content of the β transus increased. There is a part of coarse primary β grains in the alloy under the condition of II as showed in Fig.3(b), which caused by the longer heating time.

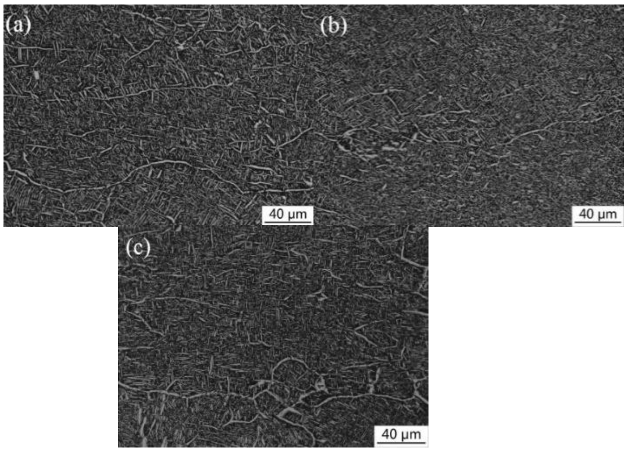

Fig.5 The microstructure of TC17 alloy at different heat-treatments($3.05\times10^{-3}s^{-1}$)
(a) 800℃/4h，WC+620℃/8h，AC；(b) 800℃/4h，WC+640℃/8h，AC；(c) 800℃/4h，WC+660℃/8h，AC

3.4 The effect of heat treatment after forging on mechanical properties

The tensile properties at room temperature after different heat treatments are shown in Tab.4. The tensile strength, ductility and shrinkage section of the TC17 alloy after the different heat treatments satisfy the technical standards. Under the system III, The yield strength is within the range of technical standards, the value of system I and system II is higher than the technical standards. It can be concluded from Tab.4, with the increase of aging temperature, the strength of the alloy decreases gradually, and the plasticity increases. When the aging temperature is rising from 620 ℃ (I) to 640℃ (II), the strength and plasticity of alloy only change a little, less than 1.1% and 5.1%, respectively. When the aging temperature is rising from 640℃ to 660 ℃ (III), the strength and plasticity of the alloy increase greatly, exceeding 7.9% and 31.7%, respectively. When the aging temperature increases, the size of secondary α phase cluster in crystal increases and distribute orientation becomes simple. The length of slip band in internal extends, the effective slip length of dislocation increases, and the extent of the direction variety decreases when the crack passes through the α cluster. So the strength reduces and the plasticity improves. What is more, with the increase of the β transus, the β matrix, BCC, has more slip flat than the α phase, and the critical stress required by the sliding surface is also lower. The atomic dense degree of BCC is lower and the cavity is easy to induce plastic deformation under shear stress. In the meantime, it also helps to reduce strength and enhance plasticity. Combining with the microstructure, it is found that the change of microstructure is more remarkable when the aging temperature increases from 640℃ to 660 ℃ than from 620℃ to 640 ℃. Therefore the change degree of the strength and plasticity is greater.

Tab.4 The room-temperature tensile properties of TC17 alloy at different heat-treatments

Heat treatment	Tensile strength σ_b/MPa		Yield strength $\sigma_{0.2}$/MPa		Elongation δ/%		Area reduction Ψ/%	
	Test	average	Test	average	Test	average	Test	average
I	1298	1296.5	1260	1259.5	11.5	10.5	22	19.5
	1295		1259		9.5		17	
II	1283	1282.5	1250	1250	11.5	11	23	20.5
	1282		1250		10.5		18	
III	1173	1176	1155	1151.5	16.0	15.0	31	27
	1179		1148		14.0		23	
technical standard	≥1120		1020-1193		≥5		≥10	

The fracture toughness results of TC17 alloy under different heat treatment are shown in Tab.5. The fracture toughness of TC17 alloy improves with the increase of aging temperature. The influence of different heat treatment on fracture toughness of TC17 is remarkable, and it has obvious regularity. The fracture toughness of the alloy meets the technical requirements only under the system III. The equiaxed α phase has stronger ability to resist crack initiation, and it is beneficial to improve fracture toughness of titanium alloy. Most of the cracks expand along the α/β interface or through α clusters in the Widmanstatten or basket-weave microstructure. Because of the different orientations of α phase cluster in β crystal, after the crack extending to the cluster boundary, it will be hindered by another α cluster if continue to expand, then have to change directions and produce branches. Thus, crack encountering clusters in different directions will cause the crack blunting and stress relaxation at its tip. It is necessary to change the direction of expansion frequently, making the path circuitous and increasing the total length of the branch and the crack. Thus, more energy need to be absorbed and fracture toughness is enhanced[8-9]. In Tab.5, fracture toughness enhances with the increase of aging temperature, closely relating to the number and size of secondary α phases and their clusters in the alloy.

Tab.5 The fracture toughness of TC17 at different heat treatments

Heat treatment	fracture toughness K_{IC}/ MPa·m$^{1/2}$
I	45.6
II	53.8
III	61.6
technical standard	≥55

Analyse the room temperature mechanical properties of alloy under three heat treatment systems, TC17 titanium alloy has preferable comprehensive mechanical properties during the heat treatment system III，that is 800°C/4h，WC+660°C/8h and air cooling. Therefore, at the strain rate of 3.05 x 10^{-3} s^{-1}, the system III can be taken as the better heat treatment system.

4. Conclusion

1. The effect of heat treatment on microstructure of TC17 alloy is mainly reflected in the difference of secondary intracrystalline α phase and β transus matrix, with the increasing of aging temperature, the size of intracrystalline secondary lamellar α phase cluster increases, orientation relationship becomes simple, and the content of β transformed structure increases.
2. The effect of aging temperature on the mechanical properties of TC17 alloy shows strong regularity, with the increasing of aging temperature, the strength of the alloy reduces, plasticity and fracture toughness increase, high cycle fatigue performance is not sensitive to the aging temperature.
3. In conclusion, TC17 under the experimental conditions of this paper, using heat treatment of 873℃/2h +918℃ /64min before forging, AC 800°C/4h,WC+660°C/8h,AC afterβ-forging, tensile properties at room temperature, fracture toughness, high and low cycle fatigue performance all meet technical requirements. The mechanical properties matches well, so heat treatment of 800°C/4h,WC+660°C/8h,AC is the better heat treatment method.

Reference

[1] Li C, Zhu M, Wang N, et al. Application of titanium alloy in airplane[J]. Chinese Journal of Rare Metals, 2009, 33(1):84-91.
[2] Leyens C,Peters M. Titanium and titanium alloys [M]. ley-VCH Verlag GmbH & Co.KGaA, 2003.
[3] Briggs R D. Tough, high-strength titanium alloys; methods of heat

treating titanium alloys: US, US8262819[P]. 2012.

[4]Yongqiang Zhang, Hongzhen Guo, Rui Liu. Microstructure and mechanical properties of isothermal forging of TC18 alloy in beta phase region [J]. Rare metal materials and EngineeringA, 2013 ,42(3):634-638.

[5] Ezugwu E 0, Bonney J, Yamane Y. An overview of the machinability of aeroengine alloys [J]. Journal of Materials Processing Technology-2003, 134 (2): 233-253.

[6] R.C. Picu, A. Majorell. Mechanical behavior of Ti-6Al-4V at high and moderate temperatures-Part II: constitutive modeling[J]. Materials Science and Engineering A, 2002, 326: 306~316.

[7] Julien Da Costa Teixeira, Benoît Appolaire, Elisabeth Aeby-Gautier, et al. Transformation kinetics and microstructures of Ti17 titanium alloy during continuous cooling [J]. Mater. Sci. Eng. A, 2007, 448: 135-145.

[8] Xiaohui Shi, Weidong Zeng, Qingyang Zhao. The effects of lamellar features on the fracture toughness of Ti-17 titanium alloy[J]. Materials Science & Engineering A, 2015, 636: 543-550.

[9] RICHARDS N L. Quantitative evaluation of fracture toughness-microstructural relationships in alpha-beta titanium alloys[J]. JMEPEG, 2004, 13: 218 -225.