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Tri-modal microstructure in high temperature toughening and low temperature strengthening treatments of near-β forged TA15 Ti-alloy

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ABSTRACT

For Ti-alloy tri-modal microstructure can be obtained by the near-β forging (water quenching, WQ) + high temperature toughening and low temperature strengthening treatment (HLT) method. However in actual production, it is hard to accomplish water quenching after near-β forging immediately. In this paper a short time of air cooling (AC) after near-β forging was introduced to consider the temperature drop during the forgings transferring in actual production. For TA15 alloy the formation process of tri-modal microstructure in near-β forging (AC + WQ) + HLT was studied. Under the given near-β forging condition, the influences of the subsequent toughening and strengthening treatment on the obtained tri-modal microstructure were revealed as well as on the corresponding mechanical properties. Then the reasonable HLT route for tri-modal microstructure with excellent comprehensive properties was determined.

1. Introduction

TA15 (Ti-6Al-2Zr-1Mo-1V) alloy is extensively used to manufacture long-duration and load-bearing structural components working below 500 °C in aircraft. It was found that for Ti-alloy a tri-modal microstructure (consisting of approximately 15–20% primary equiaxed α_p, 50–60% secondary lamellar α_s and transformed β matrix) possessed the advantages of both basket-weave and equiaxed structures and could meet the requirements in excellent mechanical properties. Zhou et al. [1] first obtained the tri-modal microstructure in TC11 alloy through near-β forging (T_β-(15–20)°C) (water quenching, WQ) + high temperature toughening and low temperature strengthening treatment (HLT) and pointed that the cooling rate after forging and the following heat treatment route had a strong impact on the morphology and distribution of precipitated α phase. However in actual production, it is hard to accomplish water quenching after forging immediately, particularly forging at a high temperature in near-β region. Transferring forgings needs some time and the forgings will be air-cooled and temperature drop will occur [2]. Gao et al. [3] found that the temperature drop during forging resulted in obvious differences in microstructure morphology and its formation process. Thus action of the temperature drop before water quenching on the final tri-modal microstructure and the corresponding mechanical properties of components needs to be discussed.

Here a new method, near-β forging (AC + WQ) + HLT, was proposed and expected to obtain tri-modal microstructure in TA15 alloy. Under this processing route the formation and evolution of tri-modal microstructure are under the coupling effects of the near-β forging (AC + WQ) and subsequent HLT. On one hand the near-β forging will affect mainly the content and distribution of equiaxed α_p [4,5]. On other hand the crystal defects and the stored distortion energy caused by near-β forging will provide possible nucleation sites and driving force for recrystallization of equiaxed α_p and precipitation of lamellar α_s. During the cooling after forging or subsequent HLT, the lamellar α_s precipitates through β → α phase transformation or decomposition of the martensite [2]. Therefore the HLT conditions (e.g., temperature, holding time, and cooling mode) not only affect the volume fraction and morphology of equiaxed α_p, but also determine the thickness, length and volume fraction of lamellar α_s. During the cooling after forging part of distortion energy and crystal defects would release accompanied by the precipitation of lamellar α_s [2], this would make the microstructure evolution to be more complicated in subsequent heat treatments. Furthermore in the tri-modal microstructure for each constituent phase there is a strict requirement of the volume fraction and morphology. Therefore for TA15 Ti-alloy the quantitative influences of the high temperature toughening and low temperature strengthening parameters on the tri-modal microstructure need to be revealed.

For near-β forging (WQ) + HLT of TA15 Ti-alloy, Sun et al. [6] and Ma et al. [7] revealed the quantitative variations in the volume fraction and morphology of equiaxed α_p and lamellar α_s in near-β deformation but the subsequent heat treatment was given (950 °C/100 min/WQ +

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800 °C/8 h/AC). Fan et al. [8] found that in isothermal local loading forming of TA15 Ti-alloy, the volume fraction of α_p was determined by heating temperature and the emergence of α_s was promoted by increasing the heating temperature or cooling rate of the last loading step. He et al. [9] studied the influences of deformation conditions on the Burgers orientation relationship and morphology during $\beta \rightarrow \alpha$ phase transformation.

As for the microstructure evolution of Ti-alloy in heat treatment, Sun et al. [10] revealed nucleation and growth mechanism of α-lamellae of TA15 cooling from an $\alpha + \beta$ phase field. Fan et al. [11] found that for TA15 alloy static globularization kinetics increased with annealing temperature while the rate of static globularization kinetics decreased with annealing time. Xu et al. [12] found that for Ti-17 alloy as holding time prolonged the size of equiaxed α_p increased while the rate of static coarsening decreased. Zhang et al. [13] found that for TA15 alloy as the annealing temperature increasing, the volume fraction of equiaxed α_p decreased and dispersed lamellar α_s gradually precipitated and coarsened. Semiatin et al. [14] pointed out that for TC4 in two phased field heat treatment a higher cooling rate resulted in an increase in content of primary α_p. Zhu et al. [15] pointed out that for TA15 the cooling rate was the decisive factor for the volume fraction, size and distribution of primary α_s. The results above show that heat treatment has a great impact on the microstructure, however most of them focused on one-step heat treatment and near-β forging before it was not involved. The main nucleation sites of α_s were grain boundaries and intracrystalline places with high-energy defects caused by deformation affected not only nucleation rate of α_s, but also atomic migration [16], furthermore influenced the precipitation and growth of α_s [5]. Zhang et al. [17] studied the dual heat treatment of TA15 alloy and discussed the effect of heat treatment temperature on microstructure and properties. Zhu et al. [18,19] discussed the dual heat treatment of a bi-modal structured TA15 alloy to obtain the tri-modal microstructure and revealed the formation and evolution of equiaxed α_p and lamellar α_s. Sun. et al. [4] conducted multi-cycle conventional forging combined with near-β heat treatment for TA15 but only a bi-modal microstructure was obtained due to the lacking of two phase field heat treatment. This indicates that each-step heat treatment is important for obtaining a tri-modal microstructure.

In this paper, a modified processing route, near-β forging (AC + WQ) + high temperature toughening and low temperature strengthening treatment, was proposed to obtain the tri-modal microstructure in TA15 Ti-alloy by considering the practical production process. The formation and quantitative evolution of tri-modal microstructure in high temperature toughening and low temperature strengthening treatment (HLT) of near-β forged (AC + WQ) TA15 alloy were investigated. The results will provide guidance for selecting reasonable HLT conditions and obtaining a tri-modal microstructure of TA15 Ti-alloy with excellent properties.

2. Material and Experimental Procedure

The TA15 alloy used in the experiments was from Western Superconducting Technologies Inc. The chemical constitution and initial microstructure of the as received TA15 alloy are the same as that in literature [6], possessing 51% primary equiaxed α with an average grain size of about 11.0 μm and an average aspect ratio of about 1.71. The β-transition temperature is 985–990 °C.

According to the actual production and results reported by Zhou et al. [1], a 60% reduction, a moderate strain rate of 0.1 s^{-1} and forming temperature of 970 °C were selected for near-β forging of TA15 alloy. In order to consider the effect of temperature drop during forging transferring in actual forming process, after deformation, the specimens were air-cooled to a certain temperature and then water-quenched.

The lamellar α_s formed in the subsequent high temperature toughening and low temperature strengthening treatment (HLT) process and the equiaxed α_s would also change in content and size. In order to analyze the effects of HLT, for toughening treatment different heating temperatures, holding time, and cooling modes should be considered. For strengthening treatment, only the heating temperature and holding time were considered, because for the forgings a cooling mode of AC was usually adopted in last hot processing step.

For Ti-alloys a two phase field (T_β-(30–60)°C) toughening treatment has been used to modify the microstructure [19–22] and for TC11 alloy the tri-modal microstructure was obtained [1]. Thus three toughening temperatures of 930 °C, 940 °C and 950 °C and toughening times of 0.5 h, 1 h and 1.5 h were selected. Meanwhile cooling modes of water quenching (WQ), air cooling (AC) and slow than air cooling (SAC) were set.

The low temperature strengthening treatment was usually according to recrystallization temperature of Ti-alloy (for TA15 alloy about 800 °C). Strengthening temperatures of 750 °C, 800 °C and 850 °C were chosen. For the sake of ensuring full precipitation of thin lamellar α phase and improving the microstructure stability [21], strengthening times of 3 h, 5 h and 8 h were adopted. Detailed experimental scheme is presented in Table 1.

The near-β deformation process was accomplished on Gleeble-3500 thermal simulation testing machine at a constant strain rate. The flat blank was processed into cylinder specimen of Φ10mm × 15 mm with 0.2 mm-deep shallow slots on the ends for storing lubricant. The specimens were heated at a rate of 5 °C/s, held for 3 min when reached the set temperature and air cooled to a certain temperature and then water quenched. When applying HLT, the heating rate is the same as the one mentioned above. After HLT, the specimens were observed by optical microscope and measured by quantitative metallographic analysis method. The measurement error of metallographic analysis is within 0.3%.

3. Formation of Tri-modal Microstructure Via Near-β Forging Combined With HLT

Fig. 1a shows microstructure of TA15 specimen after near-β forging (970 °C/0.1 s^{-1}/65%) and water quenching immediately, it contains equiaxed α_p and martensite. After subsequent high temperature toughening and low temperature strengthening treatment (HLT, 950 °C/1 h/WQ + 800 °C/5 h/AC), a tri-modal microstructure formed, consisting of equiaxed α_p, secondary lamellar α_s and transformed β matrix (Fig. 1b).

When a near-β forged (970 °C/0.1 s^{-1}/60%) specimen was cooled by air for a short time and quenched by water, the grain boundary α_{GB} precipitated and the β grain boundaries were visible (Fig. 1c). Meanwhile a good deal of Widmanstatten α_W (red rectangle) and martensite (white

Table 1
Experimental scheme.

No.	Toughening conditions	Strengthening conditions
1	930 °C/1 h/WQ	800 °C/5 h/AC
2	940 °C/1 h/WQ	800 °C/5 h/AC
3	950 °C/1 h/WQ	800 °C/5 h/AC
4	940 °C/0.5 h/WQ	800 °C/5 h/AC
5	940 °C/1.5 h/WQ	800 °C/5 h/AC
6	940 °C/1 h/AC	800 °C/5 h/AC
7	940 °C/1 h/SAC	800 °C/5 h/AC
8	940 °C/1 h/WQ	750 °C/5 h/AC
9	940 °C/1 h/WQ	850 °C/5 h/AC
10	940 °C/1 h/WQ	800 °C/3 h/AC
11	940 °C/1 h/WQ	800 °C/8 h/AC
12	940 °C/1 h/AC	–
13	950 °C/1.5 h/WQ	800 °C/5 h/AC
14	940 °C/1 h/WQ	850 °C/8 h/AC
15	950 °C/1 h/WQ	850 °C/5 h/AC

WQ—Water quenching, AC—Air cooling, SAC—Slower cooling than AC.
Forging condition: 970 °C/0.1 s^{-1}/60%/AC → 835 °C/WQ.