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ARTICLE

Effect of Heat Treatment on the Microstructure Development of TC21 Alloy

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Abstract: The microstructure development of TC21 alloy after double α/β solution and aging heat treatment was investigated. Results show that primary α phase morphology is determined by the first solution treatment at the top of α/β portion. Varying the cooling rates can significantly influence the volume fraction of retained β phase and secondary α phase. Higher cooling rate results in greater retention of the β phase and transformation of the phase into secondary α phase upon aging. This higher amount of fine secondary α phase causes higher strength and lower toughness. Second α/β heat treatment temperature remarkably influences the heat treatment response of the microstructure. Higher heat treatment temperature keeps greater amounts of β with fine transformed α in the final microstructures. Lower α/β heat treatment temperature results in less responsive retained β during aging process. Aging treatment leads to decomposition of retained β phase, particularly in larger retained β regions that exhibit lower stability.

Key words: titanium; TC21 alloy; triplex heat treatment; microstructure

TC21 alloy is a new α-β high strength and toughness alloy, and the nominal composition of the alloy is Ti-6Al-2Sn-2Zr-2Mo-1.5Cr-2Nb-0.1Si[1]. Recent experiments[2-4] have proved that the alloy exhibits high strength, high toughness and high damage tolerance. Because of wide application prospect in modern industries, it has received much attention from many materials scientists. TC21 alloy has been researched recently as a candidate material for the structural parts of advanced aircraft with an emphasis on processing microstructure relationships[5-8]. The mechanical properties of TC21 alloys essentially depend on their microstructures. Characteristics such as grain size, phase fraction, phase morphology and phase distribution, will influence the alloy properties. The microstructure is highly dependent on the thermomechanical processing conditions of the titanium alloy. In order for desired microstructure, recently, many researchers processed TC21 alloy by heat forging or heat treatment[9]. Heat treatment is one of the most efficient methods to adjust the microstructure. X. D. Zhang et al[10] indicated that triplex heat treatment, which involves β solutionizing, α/β solutionizing and aging, can obviously improve the match of strength and damage tolerance of Ti-6-22-22S. However, the β solutionizing may result in continuous β grain boundary, which is harmful for mechanical properties, especially for the fatigue and tolerance. Heat treatment at the top of α/β portion, instead of β solutionizing, can avoid these negative effects. There is little work in the field of microstructure for this innovated triplex heat treatment. In the present research, the microstructure evolution of TC21 alloy was analyzed. Anticipated outcomes of the investigation would include an improved understanding of the effects of α/β heat treatment temperature and cooling rate on the α phase morphology. In addition to developing a more complete understanding of these phenomena, a secondary objective of this study is to propose and assess alternate double solution heat treatments

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that may improve mechanical properties of it.

1 Experiment

This study examined principle components of the triplex heat treatment via their systematic variation to understand their influence on microstructure evolution. These heat treatment parameters included:

(1) Cooling rate following the first solution heat treatment at the top of α/β portion;

(2) Second α/β heat treatment temperature;

(3) Cooling rate during second α/β heat treatment.

It is important to note that in order to assess the metallographic phenomena of real industry processing, the range of double solution heat treatment parameters was selected as water quenching (WQ), air cooling (AC) and furnace cooling (FC). The raw material, TC21 alloy in the experiment was provided by Northwest Institute for Nonferrous Metals Research of China. The normal composition of the alloy was Ti-6Al-2Zr-2Sn-2Mo-2Nb-1.5Cr-0.1Si (wt%). The specimens were supplied in a hot forging condition, as shown in Fig.1. Their microstructures at room temperature are equiaxed structure. The metallographic specimens of Φ15 mm×30 mm were machined from the forging. The metallographic specimens were heated in a normal heat treatment electric muffle furnace. The sample was first α/β solutionized at 920 ℃, followed by WQ, AC and FC, and second α/β solutionized at 880 and 820 ℃ separately, followed by WQ, AC and FC, and then aged at 550 ℃, followed by AC. For optical microscope observation, the oxide of heat treated specimens were machined, and then ground with 1000 grit SiC abrasive paper and then polished with 0.05 μm alumina powder in a water suspension. The polished specimen was subsequently etched with Kroll's reagent (1 mL HF+3 mL HNO_3+5 mL H_2O) for up to 30 s. Each specimen type was metallographically characterized using a conventional optical microscopy (OLYMPUS/PMG3). Scanning electron microscopy (SEM) study of metallography was conducted on the OXFord INCI.

2 Results and Discussion

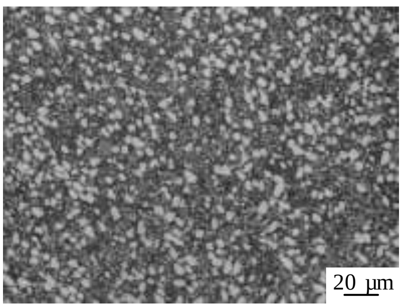

Fig.1 Optical micrograph of TC21 specimen as received

2.1 Microstructure of single α/β solution heat treatment

In order to better control the microstructure development, β phase transus temperature was determined for the received TC21 alloy. The samples were heated to 920~980 ℃ for 40 min and then water quenched. Following the standard metallography procedure, samples were examined on an optical microscope. The β phase transus temperature for TC21 alloy was determined as (945±5) ℃. For the purpose of better understanding the difference between triplex heat treatment and the traditional diplex heat treatment, the samples were heat treated at each solution temperature related in triplex heat treatment separately, and the microstructures were examined. The single solution treatments are α/β solution heat treat at 920, 880 and 820 ℃ separately, and then WQ, AC, FC to room temperature. As shown in Fig.2a, microstructure includes 10%~20% equiaxed α phase for high temperature solution treated at 920 ℃. There is no obvious difference between the water quenched and the air cooled samples, except for the tiny secondary α precipitates in β matrix for the later sample. For the furnace cooled sample, the microstructure consists of equiaxed α phase, high aspect ratio α plates and β matrix, and the size of equiaxed α phase increases obviously. The microstructures of low temperatures (880 and 820 ℃) solutionized samples are equiaxed structure, as show in Fig.2b and Fig.2c. Accompanying the decrease of cooling rate, the size of equiaxed α phase increases a little, and the volume friction of secondary α phase increases obviously, so does the decline in single solution treatment at bottom of α/β portion. The cooling rate of solution treatment can obviously affect the microstructure, especially for the high temperature heat treated sample, followed by low cooling rate.

2.2 Effects of cooling rate from α/β heat treatment

Fig.3a, 3b and 3c show the microstructures developed by the nine heat treatment combinations for the TC21 alloy. A comparison of microstructures for each respective α/β cooling rate (WQ, AC and FC) shows general similarities of microstructure that originate, in part, from the nature of the high α/β heat treated microstructures shown in Fig.2a, i.e. increasing colony morphology ratio with the decreasing α/β cooling rates. For example, for the sample that experienced only high α/β heat treatment followed by FC, the microstructures consist of an equiaxed α and α plates (Fig.2a). The proportion of plate α phase increases with the decreasing second α/β cooling rate. Optical microscopy also reveals increased fine secondary α between α plates with the decrease in second α/β cooling rate. Water quenching from 880 ℃ preserved the $\alpha+\beta$ microstructure, as show in Fig.3a. The size of α plates increases with the decrease of the first α/β heat treatment, and the size of equiaxed α changes little. It indicates that during continuous cooling from 880 ℃, nucleation of new α phase and coarsening of the existing

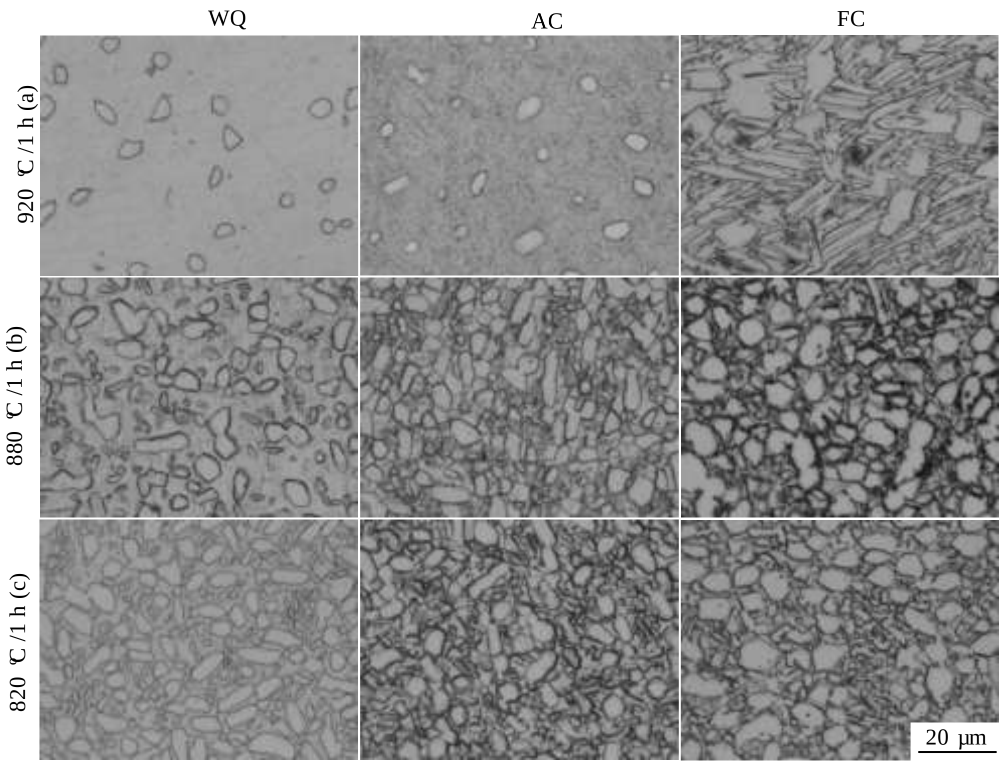

Fig.2 Optical micrographs of TC21 specimens α/β heat treated at 920 ℃/1 h (a), 880 ℃/1 h (b) and 820 ℃/1 h (c), and cooled by WQ, AC and FC

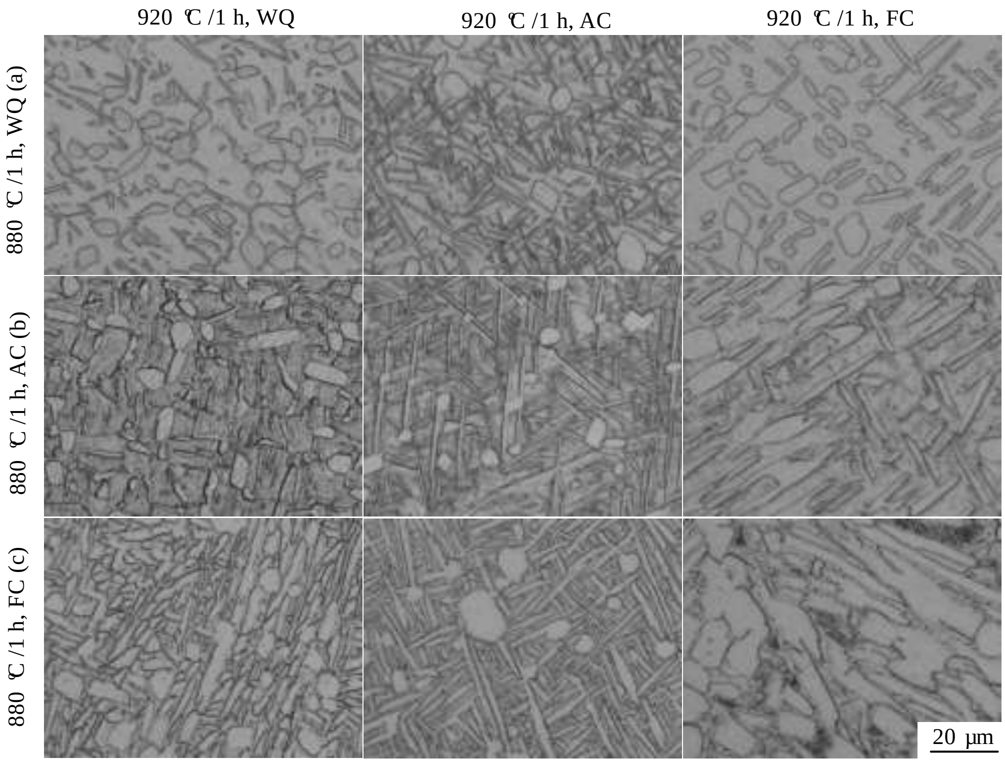

Fig.3 Optical micrographs of TC21 specimens first α/β heat treated at 920 ℃/1 h and cooled by WQ, AC, FC, and second α/β heat treated at 880 ℃ and cooled by WQ (a), AC (b) and FC (c)

α plates compete with each other, depending on the cooling rates. At slow cooling rates, the α plates have considerable time to coarsen during cooling, resulting in very thin retained β phase between the α platelets. For more rapid α/β

heat treatment cooling rate, a greater quantity of β phase is retained on cooling to low temperatures. This less stabilized β phase tends to undergo transformation to fine secondary α during subsequent aging, as show in Fig.4.

2.3 Effects of second α/β heat treatment temperature

In order to assess the influence of second α/β heat treatment temperature on the quantity and morphology of primary α phase, a series of samples were heat treated. The specimens were first α/β heat treated at 920 ℃ and cooled by AC and FC, then second α/β heat treated at 880 and 820 ℃, separately, followed by WQ, AC and FC. The water quenching of these specimens from the heat treatment temperature promotes transformation of the β phase to extremely fine martensite. Fig.5 and Fig.6 show optical micrographs for some of these specimens quenched from 880 ℃ and 820 ℃. The appreciable equiaxed α phase and α plates remain after second solutionizing at the bottom of α/β portion.

Note that all of the microstructures are tri-modal structure, and one of the most obvious differences is the width of α plates. The characteristics of the microstructures are consistent with the β isomorphous type phase diagram exhibited by Ti-Al-β stabilizer systems containing isomorphous and sluggish β-eutectoid formers. These indicate that a decrease in second α/β heat treatment temperature would promote a lower proportion of β phase that is more highly enriched in β-stabilizer content. Consequently, for 820 ℃ heat treated specimen cooled by WQ, the microstructure is composed of α and retained β phase. For higher second α/β heat treatment temperatures and a rapid cooling rate, a greater proportion of less stable β phase exists at peak temperature which, in turn, transforms on cooling to fine, secondary α, or is retained for subsequent decomposition during aging heat treatment.

As mentioned in the previous section, slow cooling rates during second α/β heat treatment, allows growth of the α phase on cooling, and increases stability and retention of the remaining β phase. Though the slow cooling rate of second α/β heat treatment results in thicker α plate, which is positive for damage tolerance, the over slow cooling rate is harmful for ageing responsibility. So the ideal heat treatments should result in thick α plates and proper remaining β phase, for which the ageing strengthening will be neither too sensitive nor insensitive. As shown in Fig.6b, the microstructure of 920 ℃/1 h, FC+820 ℃/1 h, AC heat treated specimen may be the best candidate. The actual effects of this heat treatment need to be examined in the future.

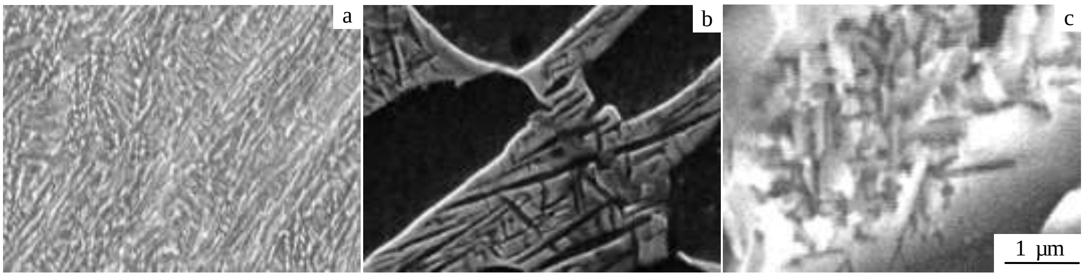

Fig.4 SEM images of TC21 specimens first α/β heat treated at 920 ℃/1 h, WQ, and second α/β heat treated at 880 ℃ cooled by WQ (a), AC (b), FC (c), and then aged at 550 ℃/6 h, AC

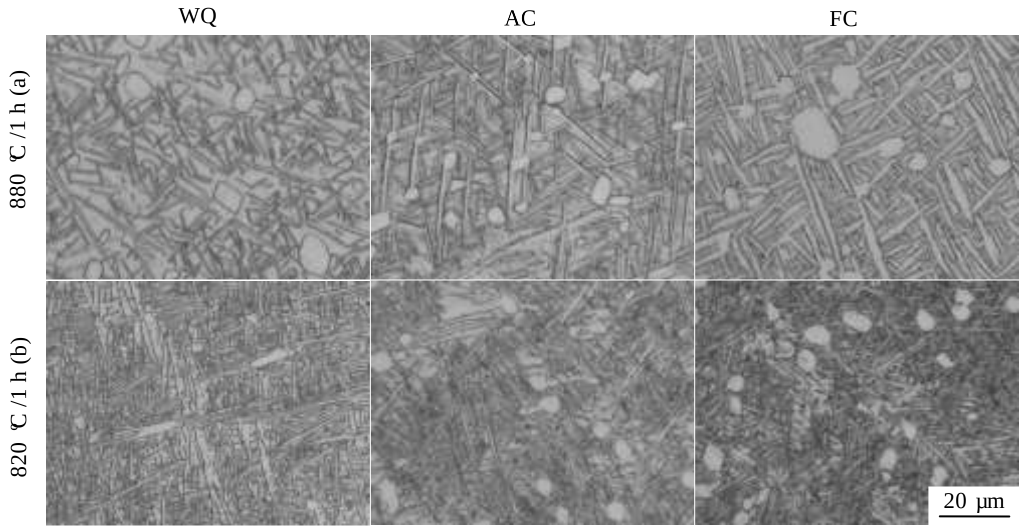

Fig.5 Optical micrographs of TC21 specimens first α/β heat treated at 920 ℃/1 h, AC, and second α/β heat treated at 880 ℃ (a) and 820 ℃ (b), and cooled by WQ, AC, FC

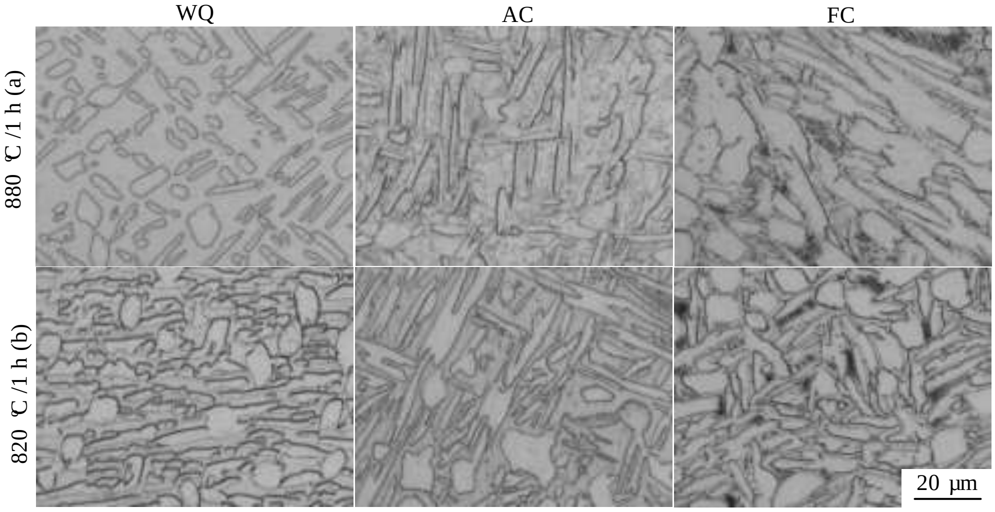

Fig.6 Optical micrographs of TC21 specimens first α/β heat treated at 920 ℃/1 h, FC, and second α/β heat treated at 880 ℃ (a) and 820 ℃ (b), and cooled by WQ, AC, FC

3 Conclusions

1) Primary α morphology is determined by the first solution treatment at the top of α/β portion. Varying the cooling rates can significantly influence the volume fraction of retained β phase and secondary α.

2) Second α/β heat treatment temperature significantly influences the heat treatment response of the microstructure. High heat treatment temperatures promote greater amounts of retained β with fine, transformed α in the final microstructures. Lower α/β heat treatment temperatures promotes retained β microstructures which are less responsive to aging heat treatment.

3) The double α/β solution heat treatment 920 ℃/1 h, FC +820 ℃/1 h, AC can result in tri-modal structure with thick α plates and proper remaining β matrix.

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热处理对 TC21 钛合金显微组织的影响

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摘　要：对TC21钛合金进行双重固溶+时效热处理，研究固溶冷却速率、温度对合金显微组织的影响。研究表明，初生α相形貌主要受一次高温固溶温度控制，高温固溶冷却速率对次生α相含量及长宽比有显著的影响。高的固溶冷却速率可以保留更多的亚稳定β相，从而在时效过程析出更多细小的次生α相，导致强度增加，塑性及韧性下降。二次低温固溶温度对合金后续的时效响应有显著的影响，高的固溶温度可以保留更多的β相，促使更多细小的转变α相在时效中析出；低的固溶热处理温度导致固溶残余β相含量减小，时效敏感性降低。时效过程导致残余β相的分解，特别是大块亚稳定β相区。

关键词：钛；TC21 钛合金；三重热处理；显微组织

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