

Alloying elements characterization in a Ti-5.6Al-4.8Sn-2Zr-1Mo-0.35Si-1Nd titanium alloy by carbon addition

Shangzhou Zhang¹⁾, Huizhong Xu¹⁾, Ziquan Liu¹⁾, Huilu Li¹⁾, and Rui Yang²⁾

1) School of Environmental and Materials Engineering, Yantai University, Yantai 264005, China

2) Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

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Abstract: The effects of carbon addition (0.01wt%-0.43wt%) on a Ti-5.6Al-4.8Sn-2Zr-1Mo-0.35Si-1Nd (wt%) alloy with a bimodal microstructure were investigated. Electron probe microanalysis was carried out to examine the partitioning behavior of carbon and the relation of carbon content to the distributions of Al and Mo in the primary α phase (α_p) and β transformed structure (β). It was found that interstitial carbon is enriched in the α_p phase and its content slightly reduces with the increase of the volume fraction of α_p . The measurements of carbon content in the present alloy with an α_p of 15vol% showed that the carbon content in the α_p phase increases with the increment of carbon addition until a maximum but keeps almost constant in the β phase. The addition of carbon reduces the solubility of Al and Mo in the α_p phase and leads to the increment of Mo partitioning to the β phase. When the carbon content is over 0.17wt% (0.67at%), carbide precipitation occurs in the matrix and its volume fraction is related to the volume fraction of α_p , which can be explained in term of the difference of carbon solubility in the α_p and β phases.

Key words: high-temperature titanium alloy; carbon; alloying elements; partitioning

1 Introduction

Near- α titanium alloys remain excellent candidates for aero-engine critical parts such as compressor discs and rotors owing to good property retention and creep resistance at elevated temperature. Extensive researches have been conducted to identify the relationships between microstructure and mechanical properties [1-3]. A wide range of properties is obtainable by varying the microstructure through thermomechanical processing. The alloys with bimodal microstructures usually exhibit a unique combination of strength, creep resistance, and fatigue properties. Elemental partitioning between bimodal microstructures has an important effect on the mechanical properties [4], and an optimal combination of the mechanical properties can be obtained for the microstructure with about 15vol% of primary α (α_p) in a transformed β matrix [5].

A Ti-5.6Al-4.8Sn-2Zr-1Mo-0.35Si-1Nd (wt%) alloy was developed to meet the increasing requirements of rotating components in the compressor part of aero-engines. This alloy after being processed in the (α + β) two-phase field is characterized by a bimodal microstructure with a small amount of the α_p phase, which is very important for improving the fatigue strength and the creep resistance. For high-

temperature titanium alloys, however, the (α + β) processing window is relatively small [6-7], that is, the change of the volume fraction of α_p is fast as the solution temperature approaches the (α + β)/ β transus temperature. To minimize this drawback interstitial carbon has been used as alloying addition to widen the range of temperature for heat treatment in the high (α + β) phase region [8-9]. Carbon affects not only the change of the volume fraction of α_p but also the partitioning of alloying elements between the α_p and β phases. The knowledge for the composition of each phase of the bimodal microstructure is necessary for a proper interpretation of the mechanical properties. It is the objective of the present work to clarify the relation of carbon to the microchemistry and microstructure of a Ti-5.6Al-4.8Sn-2Zr-1Mo-0.35Si-1Nd so as to properly evaluate the microstructural stability of this type of alloys.

2 Experimental

The material used as the base alloy in this work was prepared by consumable electrode arc melting. The base alloy was hot-rolled to bars ϕ 20 mm from a 500kg ingot in the (α + β) region at 980°C. The different amounts of carbon, 0.24at% (0.06wt%), 0.67at% (0.17wt%), 0.91at% (0.23wt%), 1.26at% (0.32wt%) and 1.67at% (0.43wt%), were added to the base alloy

as alloying element. The contents of carbon are given in atomic fraction in the following sections except specified otherwise. Alloys containing carbon were prepared by melting the base alloy and graphite powder with a tungsten arc in a water-cooled crucible under an argon atmosphere. Buttons of about 60 g in mass were obtained and remelted four times to guarantee homogenization of the alloys.

The buttons were finish-forged in the $(\alpha+\beta)$ phase field to produce $\phi 10$ mm bars with an equiaxed primary α structure. To obtain the desired microstructures, the samples were then heat-treated in the $(\alpha+\beta)$ phase field followed by air cooling to produce bimodal microstructures with different volume fractions of α_p .

Metallographic specimens were prepared by the conventional method. The heat-treated specimens were subjected to microstructural examination and microchemical analysis employing a JSM6301F scanning electron microscope (SEM) and an EPM810 electroprobe microanalyser (EPMA). The latter was performed using point analysis on the metallographic surface of individual phases. The minimum of 10 points was analyzed for each phase. Transmission electron microscopy (TEM) was performed on thin foil specimens using an EM-420 microscope. Thin foils were prepared by the twin-jet electropolishing technique in a solution of 21% perchloric acid, 50% methanol and 29% n-butyl alcohol at -40°C .

3 Results and discussion

Figure 1 shows a set of three typical microstructures of the 0.67at% C alloy illustrating the effects of air cooling from temperatures of 990°C , 1070°C and 1100°C . Solution treatment in the $(\alpha+\beta)$ phase field leads to a bimodal microstructure consisting of globular primary α and rare earth particles in a transformed β matrix. The solution treatment temperature determines the volume fractions of α_p and the transformed β matrix. The highest temperature yields the smallest volume fraction of the α_p . Solution treatment at 990°C followed by air cooling leads to a α_p content of about 75vol% while increasing the solution temperature to 1100°C results in a α_p content of approximately 15vol%.

The contents of the alloying elements C, Al and Mo in the α_p and β phases as a function of the volume fraction of α_p for the 0.67at% C and 1.26at% C alloys are presented in **figure 2**. The distributions of Zr, Sn, Si and Nd are not shown in figure 2 because Zr, Sn and Si are almost uniformly distributed between the α_p and β phases. The element Nd can not be detected by EPMA because the solubility of Nd in the matrix is

very low and most of it is contained in the rare-earth particles, one of which is indicated in figure 1(a).

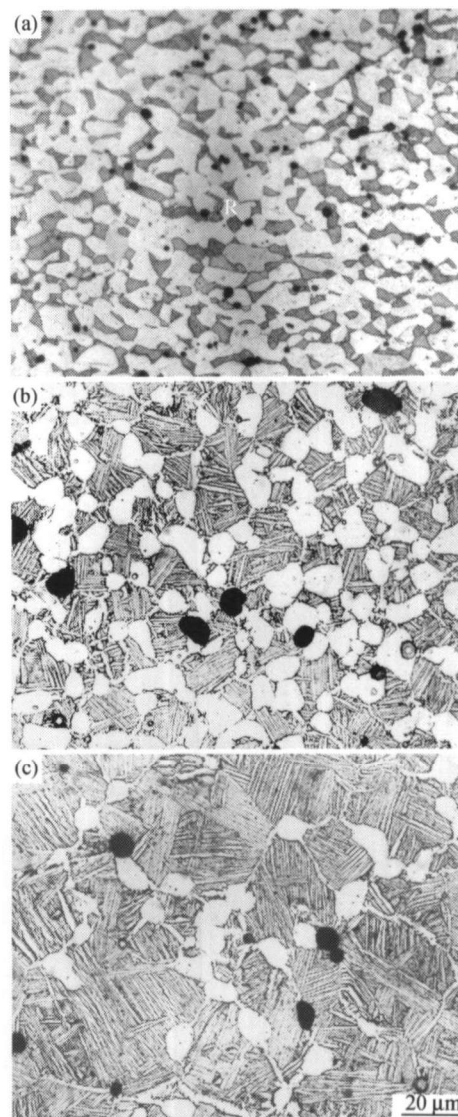


Figure 1 Microstructures of the 0.67at% C alloy heat treated in the $\alpha+\beta$ phase field followed by air cooling, a rare earth particle is marked by R: (a) 990°C ; (b) 1070°C ; (c) 1100°C .

The results in figure 2 indicate that the partitioning behaviors of alloying elements to α_p and β are similar for the two alloys. The solubility of carbon in the α_p and β phases is very low and carbon preferentially partitions to the α_p phase. The carbon content in the α_p phase increases with decreasing the volume fraction of α_p while in β it appears independent of the relative amount of phases. Al partitions to α_p and Mo to the β phase as expected. The partition of Al to α_p is almost independent of its volume fraction and thus the α_p phase essentially consumes a fixed fraction of Al; the partition of Al to β decreases with increasing the volume fraction of α_p . There is notable increase in the partition of Mo to β , but that to α_p increases only very slightly with the increase of the volume fraction of α_p ,

suggesting that the α_p phase has a limited solubility for Mo and explains the increase in Mo content in β phase.

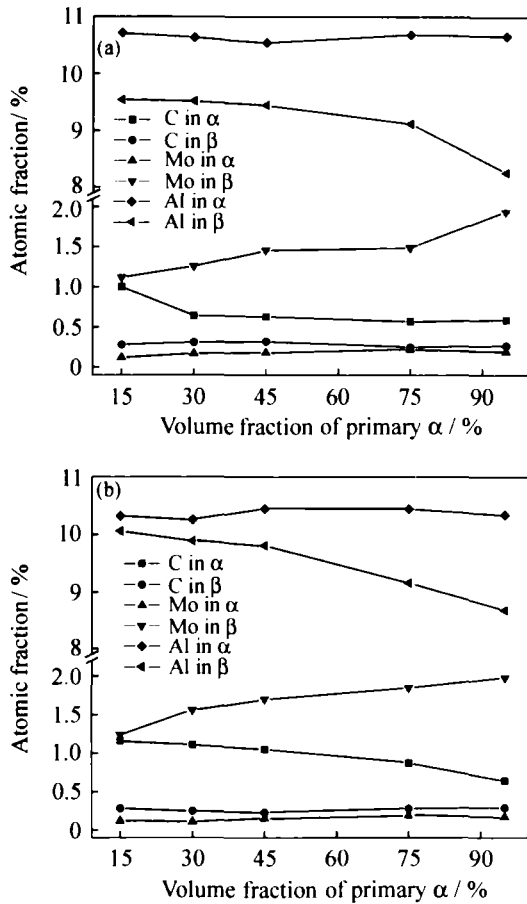


Figure 2 Average contents of C, Al and Mo in the primary α and β for the experimental alloys as a function of the volume fraction of the primary α : (a) the 0.67at% C alloy; (b) the 1.26at% C alloy.

To identify the relation of carbon to the distribution of alloying elements in the present alloys, the partition of alloying elements between the two phases α_p and β for the alloys containing the α_p phase of about 15vol% was measured by EPMA analysis. The results are given in **figure 3**. These results indicate that the carbon content in the α_p phase levels off when the carbon addition exceeds 0.67at% while in β it is nearly the same for all alloys. The difference of carbon content in the α_p and β phases becomes large gradually with the increase of carbon up to 0.67at%.

The addition of carbon actually decreases the content of Al in the α_p phase and increases the partitioning of Mo and Al to the β phase, but has no effect on the distributions of Zr, Sn and Si (not shown here). Although the extents of partitioning of Al and Mo to the β phase increase with the increase of carbon content, the Al content in the α_p phase is still higher than that in the β phase. As the carbon addition is over

1.26at%, the Al content in the α_p and β phases is almost invariant. The Mo content in the α_p phase is reduced initially by the addition of 0.24at% carbon and then no further drop in Mo content occurred with the increase of carbon.

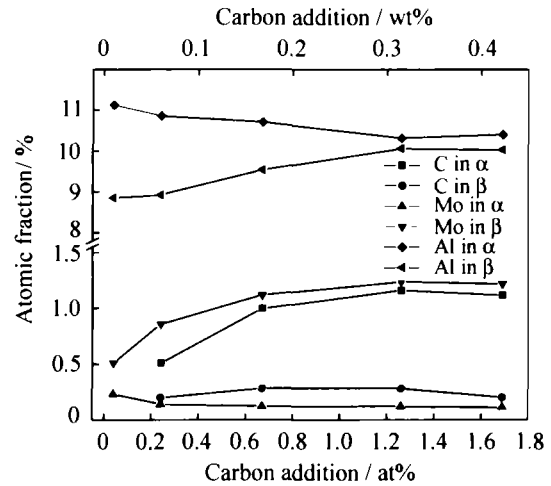


Figure 3 Comparison of C, Al and Mo contents in the α_p and β phases in the alloys with different carbon contents at about 15vol% of α_p .

Alloying additions to titanium can be classified as α stabilizers (e.g., Al, O) or β stabilizers (e.g., Mo). In this results the anticipated preference of Al for the α_p phase and Mo for the β matrix was confirmed, while the neutral elements Zr and Sn were observed to show compositional uniformity across the α_p and β phases, in good agreement with the previous reports [10-11].

The experimentally determined contents indicate that interstitial carbon is significantly less soluble in the β phase than in the α_p phase. Since carbon is an α stabilizer it is expected to partition to the α_p phase. Therefore it is the supersaturation in the β phase that promotes the carbon atoms to enter the α_p phase. Since the content of carbon in the β phase is nearly the same for all the alloys, independent of the volume fraction of α_p , it can be regarded as the maximum solubility of carbon in this phase. The carbon content in the α_p phase falls with increasing the volume fraction of α_p , so it can be tentatively concluded that the maximum solubility of carbon in the α_p phase is about 1.16at%.

Figure 3 shows that carbon increases the partitioning of Mo to the β phase and decreases the Al content in the α_p phase. At lower carbon content, the α_p phase has greater solubilities of Al and Mo, but the contents of the other alloying elements are less affected. Flower *et al.*[11] found that the addition of Si to IMI550 inhibits the partitioning of Mo to the β phase. There are other reports [12] of the addition of nitrogen to Ti-6Al-4V and Ti-17 alloys as well as nitriding of Ti-

6Al-4V. It was found that the addition of nitrogen up to 18% reduces the solubility of Al in α -Ti to such a degree that the content of Al in α -Ti falls below that in β -Ti, and the partitioning to the β phase of both Mo and Cr in Ti-17 as well as V in Ti-6Al-4V increases. These trends are similar to this result, although the Al content in the α_p phase remains higher than that in the β phase in the present alloys, possibly due to the smaller solubility of carbon than nitrogen. To sum up, it is concluded that interstitial carbon or nitrogen promotes more uniform distribution of Al between the α_p and β phases, but increases the segregation of β stabilizers such as Mo, V and Cr to the β phase. The relevance of the conclusion to long-term high-temperature service of near- α titanium alloys is that alloying with these elements would delay the precipitation of the α_2 from the α_p phase, and therefore would reduce exposure-related embrittlement of the alloys.

When the carbon addition exceeds 0.67at%, carbide precipitation occurs in order to meet the requirement of a thermodynamic equilibrium. Figure 4 shows the phases of the 1.26at%C alloy heat-treated at 1180°C for 4 h, as identified by X-ray diffraction: Both α -Ti and TiC were detected but the amount of β is too small and gives only very weak diffraction intensities. The measurement of the saturation level of carbon in each phase presented above allows the deduction of the relation of the volume fraction of carbide with the volume fraction of α_p for the alloys containing different amounts of carbon as shown in figure 5. Two prominent features of these plots can be seen. First, no carbide formation occurs if the volume fraction of α_p is maintained above a certain level. Only beginning from 0.67at%C did the carbides appear in the Widmanstätten structure of transformed β ; for the 0.91at%, 1.26at% and 1.67at%C alloys, the carbide particles could be observed in the (α + β) microstructure when the volume fraction of α_p is lower than 8.5vol%, 24vol% and 34vol%, respectively.

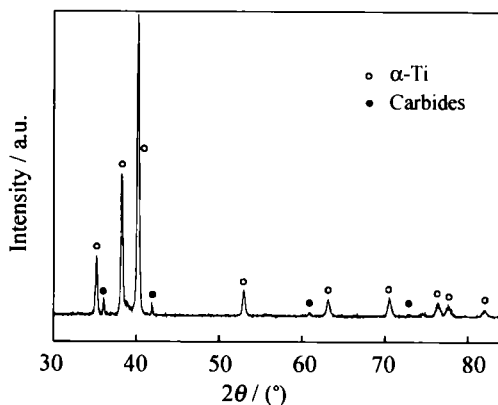


Figure 4 Phases identified by X-ray diffraction in the 1.26%C alloy heat-treated at 1190°C for 4 h.

Second, the volume fraction of α_p significantly influences the amount of carbide precipitation, as can be seen from the relatively steep curves of figure 5. The fully Widmanstätten microstructure without α_p contains the maximum volume fraction of carbides. As expected, a higher carbon level in the alloy corresponds to a larger amount of carbides. Changes in microstructure with the increase in the volume fraction of α_p for the 1.26at%C alloy are shown in figure 6. Large carbide particles can be seen from the SEM images; in addition, detailed TEM examinations indicated that fine carbide precipitates not discernable from figure 6 are present in all the microstructures. Carbide particles preferentially form from the β transformed grains of the bimodal microstructure. The observation of the increasing volume fraction of carbides with decreasing the volume fraction of α_p , shown in figure 6, accords with the deduction based on composition measurements presented in figure 5. Thus by controlling the volume fraction of α_p , the amount of carbide precipitation can be varied.

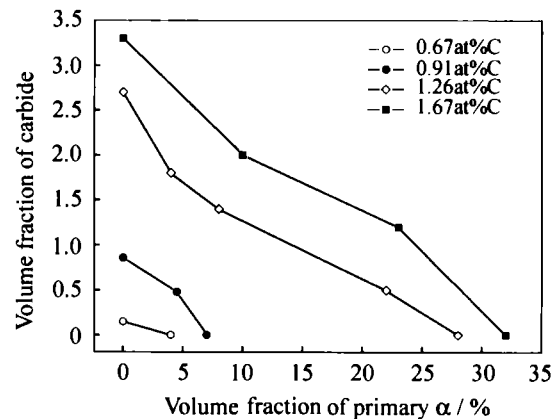


Figure 5 Variation of the volume fraction of carbides with that of the primary α in the alloys containing different carbon contents under the air-cooled condition.

4 Conclusions

The partitioning behavior of alloying elements to the two phases of the bimodal microstructure of the present alloys with different amounts of carbon was investigated using EPMA. Carbon was found to be mostly confined to the α_p phase. For an α_p content of 15vol%, the carbon content in the α_p phase increases with the increment of carbon addition until a maximum but remains almost constant in the transformed β phase. The addition of carbon reduces the solubility of Al in the α_p phase and increases the Al and Mo contents in the transformed β phase, but has no effect on the distributions of Zr, Sn and Si. For the carbide precipitation from the bimodal microstructures, its volume fraction is determined by that of the α_p phase, and

this dependence can be explained by the difference of

carbon solubility in the α_p and β phases.

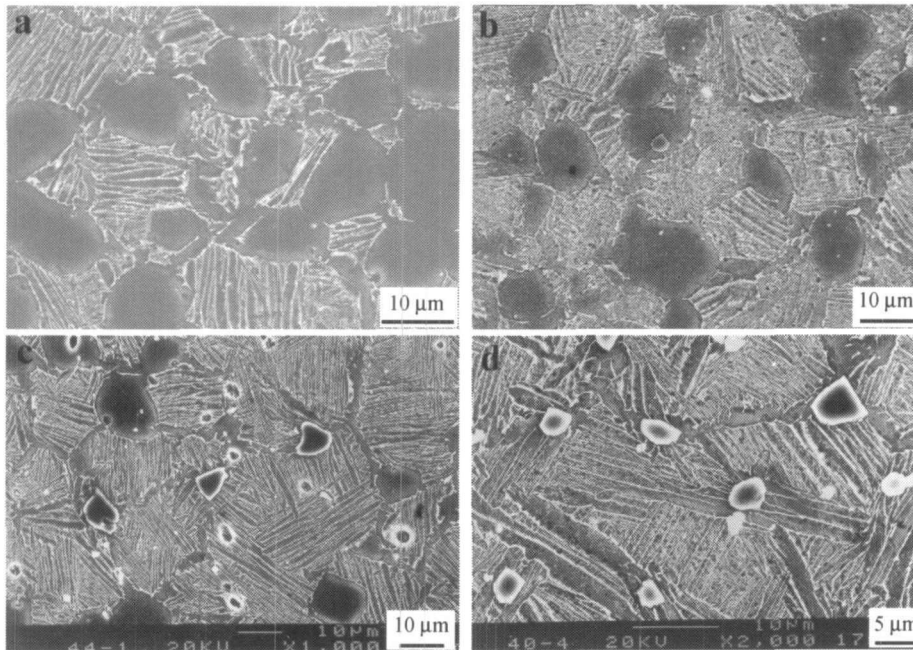


Figure 6 SEM micrographs showing the carbide formation as a function of the volume fraction of α_p in the 1.26at% C alloy: (a) 30vol%; (b) 22vol%; (c) 8vol%; (d) 0vol%.

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