Effect of Solution Treatment on Microstructure and Selected Mechanical Properties of an (α+β) Titanium Alloy

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Abstract. The influence of solution treatment on the microstructure and mechanical properties of an (α+β) high temperature titanium alloy (Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si) are investigated by optical microscope (OM), scanning electron microscopy (SEM), electron probe microanalysis (EPMA) and tensile tests at room and elevated temperatures. The results shows that, Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si alloy after simple solution treatment has good combinations of plasticity and tensile strength both at room and high temperature. With the solution temperature increasing, the volume fraction of primary α phase (αp) decreases gradually, while the volume fractions of β matrix (βt) and secondary α phase (αs) increase. Room and high temperature tensile properties are insensitive with microstructure after solution treatment. With the solution temperature increasing, the content of αp phase decreases while the content and size of βt increase, which would cause the strength increase and plasticity decrease at RT and 650°C.

1. Introduction
High temperature titanium alloy has high specific strength, good thermal strength and excellent corrosion resistance, is widely used in aerospace, such as compressor disks and blades of gas turbines of advanced jet engines [1, 2]. At present, the highest using temperature of titanium alloy applied at home and abroad is 600°C. Typical examples are IMI834 [3], Ti1100 [4], BT36 [5], Ti60 [6] and Ti600 [7]. With the service temperature increasing, the creep resistance and oxidation resistance of high temperature titanium alloy gradually decreases. Therefore, development of titanium alloys working more than 600°C becomes difficult. Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si alloy belongs to (α+β) titanium alloy, with outstanding high temperature properties, is designed for high temperature applications up to 650°C. As we know, the mechanical properties can be very strongly dependent upon the microstructure (such as the content and shape of primary α phase (αp), secondary α phase (αs) and precipitation), which in turn is specific to the applied heat treatment [8]. If the relationship between microstructure and mechanical properties of an alloy is established and understood, it will be very convenient to get desirable combination of properties by heat treatment. The objective of this work is to research the effects of solution treatment on the microstructure and mechanical properties of Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si alloy.

2. Experimental procedure
The Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si alloy ingot was melted three times by triple vacuum consumable electrode method. Breakdown forging of the ingot was carried out in β phase region to 65mm square cross-section billet, and then hot forged into bars of 12 mm diameter at 900°C followed by air cooling. β-transus temperature of this alloy was measured to be 960–970°C by metallographic examination.

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techniques. The tested alloy was solution treated at 900°C, 920°C, 940°C and 960°C for 2h, following by air cooling (AC).

Microstructures were observed by Axiovert 200 MAT Zeiss optical microscopy (OM) and JSM-7001F scanning electron microscope (SEM). The specimens for OM and SEM observation were mechanically polished with the standard metallographic producer and etched in the Kroll’s reagent. The phase compositions were measured by JXA-8100 electron probe microanalyzer (EPMA). Round standard samples with a diameter of 5 mm and a gage length of 25 mm were used for tensile tests. Room temperature (RT) and 650°C tensile tests were conducted on an Instron 5582 testing machine equipped with a heating furnace at a strain rate of 0.04/min and 0.005/min, respectively. Three specimens were tested to get an average.

3. Results and discussion

3.1 Effect of solution treatment on microstructures

The OM and SEM micrographs of the investigated alloys solution treated at different temperature are shown in Figure1. It can be seen that all of them are bi-modal microstructures consist of equiaxed αp and lamellar βt. Image-Pro Plus 6.0 software are used to measure the microstructural parameters, including the size and volume fraction of αp, the size of βt and αs. Increase in the solution temperature leads to a decrease in the volume fraction of αp in the microstructure, and also there appears an increase in the content and size of βt and αs, this phenomenon is in accordance with the results of other researchers [9, 10].

Table 1 lists the concentration of alloying elements measured by EPMA. It can be found that the content of Al in αp is higher than that in βt, While the contents of Sn, Zr, Mo, W, Si are less than in βt, especially the β stabilizing elements Mo and W. The author has been studied that Mo is more inclined to dissolve in β phase than α phase [11]. In addition, with the solution temperature increasing, the contents of Al in each phase increase, while β stabilizer elements decrease.
Figure 1. Microstructures of Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si alloy solution treated at different temperature: (a) (b) 900°C, (c) (d) 920°C, (e) (f) 940°C, (g) (h) 960°C

Table 1. Elements concentration in each phase of Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si alloy after annealing at different temperature

| Solution Temperature | Phase | wt%  |
|----------------------|-------|------|
|                      |       | Al   | Sn   | Zr   | Mo   | W    | Si   |
| 900°C                | α₀    | 7.387| 2.005| 3.409| 1.073| 0.187| 0.168|
|                      | β₀    | 6.342| 2.130| 3.619| 7.565| 1.333| 0.138|
| 920°C                | α₀    | 7.831| 2.049| 3.418| 1.072| 0.180| 0.170|
|                      | β₀    | 6.566| 2.110| 3.423| 7.459| 1.244| 0.14 |
| 940°C                | α₀    | 7.716| 1.987| 3.270| 0.753| 0.170| 0.173|
|                      | β₀    | 6.585| 2.206| 3.433| 6.218| 1.192| 0.184|
| 960°C                | α₀    | 8.162| 2.032| 3.169| 0.713| 0.111| 0.183|
|                      | β₀    | 6.658| 2.120| 3.548| 5.944| 1.083| 0.196|
3.2 Effect of solution on RT tensile properties

The RT tensile properties of Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si alloy after solution treated at different temperature are studied. Figure 2 gives the relationships among tensile strength ($R_m$), yield strength ($R_{p,0.2}$), elongation (A) and solution temperature. It can be seen that this alloy has excellent performance at RT, the $R_m$, $R_{p,0.2}$ and A of this alloy are more than 1300MPa, 1200MPa and 15%, respectively. With the solution temperature increasing, the strength increases and plasticity decreases.

![Figure 2. Room temperature tensile properties of the investigated alloy after solution treated at different temperature](image)

3.3 Effect of solution on 650°C tensile properties

Figure 3 shows the relationship between the mechanical properties and solution temperature. The $R_m$, $R_{p,0.2}$ and A of this alloy can reach more than 750MPa, 500MPa and 30% at 650°C, respectively. With the solution temperature rising, tensile strength of the alloy increases and plasticity decreases gradually. It's known that boundary strength and grain strength decrease as deformation temperature increasing. Since boundary strength decreases more rapidly, grain strength is higher than boundary strength at higher temperature [12]. It is attributed to the movement of boundaries at higher temperature. T. Wang et al. have proved that the movement of boundary in TG6 at 600°C [13]. So the activity of boundaries in our investigated materials is remarkable during 650°C tensile process, leading to a big decline in boundary strength. As shown in Fig. 1, with solution temperature increasing, content of $\alpha_p$ phase decreases while the content and size of $\beta$, increase, which would decrease the number of $\alpha$/$\beta$ phase boundary. J.S. Kim has demonstrated that the sliding resistance of $\alpha$/$\beta$ phase boundary is less than that of $\alpha$/$\alpha$ and $\beta$/$\beta$ phase boundaries at high temperature [14]. So the decrease in the content of $\alpha$/$\beta$ phase boundary would increase the strength at high temperature.
Figure 3. 650°C tensile properties of the investigated alloy after solution treated at different temperature

4. Conclusions
1) Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si alloy after simple solution treatment has good combinations of plasticity and tensile strength both at room and high temperature. After simple solution treatment, the $R_m$, $R_{p0.2}$ and A of this alloy can reach more than 750MPa, 500MPa and 30% at 650°C, respectively.

2) Increase in the solution temperature leads to decrease in the volume fraction of α_p and increase in the content of β_t and α_s, the sizes of these phases become coarse. Meanwhile, the contents of Al in each phase increase, and the β stabilizer elements decrease, as solution temperature increasing.

3) Room and high temperature tensile properties are insensitive with microstructure after solution treatment. With the solution temperature increasing, the content of α_p phase decreases while the content and size of β_t increase, which would cause the strength increase and plasticity decrease at RT and 650°C.

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6. References
[1] Liu Y, QU Z.D., Wang B., Research development and application of Ti6A14V alloy, Ordnance Material Science and Engineering, 2005, 28 (5): 48–50.
[2] Wang T., Guo H.Z., Wang Y.W., Peng X.N., Zhao Y., Yao Z.K., The effect of microstructure on tensile properties, deformation mechanisms and fracture models of TG6 high temperature titanium alloy, Materials Science and Engineering A, 2011, 528: 2370–2379.
[3] Wanjara P., Jahazi M., Monajati H., Yue S., Immarigeon J.P., Hot working behavior of near α alloy IMI834, Materials Science and Engineering A, 2005, 396: 50–60.
[4] Madsen A., Ghonem H., Effects of aging on the tensile and fatigue behavior of the near α Ti1100 at room temperature and 593°C, Materials Science and Engineering A, 1994, 177: 63–73.
[5] Hao M.Y, Cai J.M, Du J., The effect of heat treatment on microstructure and properties of BT36 high temperature alloy, Journal of Aeronautical Material, 2003, 23(2): 14–17.
[6] Jia W.J., Zeng W.D., Zhou Y.G., Liu J.R., Wang Q.J., High temperature deformation behavior of Ti60 titanium alloy, Materials Science and Engineering A, 2011, 528: 4068–4074.
[7] Niu Y., Li M.Q., Effect of 0.16 wt% hydrogen addition on high temperature deformation behavior of the Ti600 titanium alloy, Materials Science and Engineering A, 2009, 513/514:228–232.
[8] Banerjee D., Williams J., Microstructure and slip character in titanium alloys, Defence Science Journal, 2014 (36): 191-206.
[9] Thiehsen K.E., Kassner M.E., Pollard J., Hiatt D.R., Bristow B.M., Manufacturing process and mechanical properties of fine TiB dispersed Ti-6Al-4V alloy composites obtained by reaction sintering, Metallurgical Transaction A, 1993 (24): 1819-1826.
[10] Bania P.J., Hall J., Titanium Science and Technology, 1985, pp. 2371-2378.
[11] Zhang W.J, Song X.Y., Hui S.X., Ye W.J., The effects of Mo content on microstructure and high temperature tensile behavior of Ti-6.5Al-2Sn-4Zr-xMo-2Nb-1W-0.2Si titanium alloys, Materials at high temperature, 2017, 34 (3): 179-185.
[12] Wang Y.L., Song X.Y., Ma W., Zhang W.J., Ye W.J., Hui S.X., Microstructure and tensile properties of Ti-62421S alloy plate with different annealing treatments, 2014: 1-6.
[13] Wang T., Guo H. Z., Wang Y.W., Peng X.N., Zhao Y., Yao Z. K., The effect of microstructure on tensile properties, deformation mechanisms and fracture of TG6 high temperature titanium alloy. Materials Science and Engineering A, 2011 (528): 2370-2379.
[14] Kim J.S., Kim J.H., Lee Y.T., Park C.G., Lee C.S., Microstructural analysis on boundary sliding and its accommodation mode during superplastic deformation of Ti - 6Al - 4V alloy, Materials Science and Engineering A, 1999 (263): 272 – 280.