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Oxygen Effects on the Mechanical Properties and Lattice Strain of Ti and Ti-6Al-4V

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The effects of oxygen on the mechanical properties and the lattice strain of commercial pure CP) Ti and Ti-6Al-4V alloys are discussed here in terms of the Vickers hardness, tensile strength and elongation. The Vickers hardness and tensile strength of the CP Ti and the Ti-6Al-4V alloys increased with an increase in the oxygen concentration. On the other hand, the elongation of the CP Ti decreased considerably as the oxygen concentration increased, while that of the Ti-6Al-4V alloys gradually decreased as the oxygen concentration increased. Thus, the oxygen concentration has a greater effect on the mechanical properties of CP Ti compared to its effects on the Ti-6Al-4V alloy. This can be explained in terms of the difference in the solid solution effect of oxygen between the CP Ti and the Ti-6Al-4V alloy. Where, the mechanical properties of Ti-6Al-4V alloy were previously affected by an earlier lattice expansion caused by an increment in the *c*/*a* ratio of the Ti-6Al-4V during the Al and V alloying process.

Keywords: alloys, melting, mechanical properties, hardness test, X-ray diffraction

1. INTRODUCTION

Since Ti and Ti alloys have high strength, low density and excellent corrosion resistance, it has been used as an important material in modern industry [1]. The mechanical properties of Ti and Ti alloys strongly depend on interstitial elements such as oxygen [2]. In addition, oxygen is a standard element in the ASTM mechanical strength level classification of pure Ti. Generally, solid solution hardening is well known as the most common hardening effect of Ti by oxygen [3]. Anderson *et al.* [4] noted that the oxygen content in Ti can show more lattice strain in the *c* direction than in the *a* direction. Thus, the *c*/*a* ratio of hcp Ti changes and the restricted dislocation motion affects the hardening of the Ti. Several researchers have studied the effects of oxygen on the properties of the solid solution phase of pure Ti [5,6], however, detailed reports of differences in the effects of oxygen on the mechanical properties and related lattice strain of pure Ti and Ti-6Al-4V alloy are rare. Therefore, we investigated the differences in the solid solution effect of oxygen between pure Ti and Ti-6Al-4V alloy in terms of the Vickers hardness, tensile strength, elongation and related lattice strain.

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2. EXPERIMENTAL PROCEDURE

To prepare Ti-6Al-4V alloys with different oxygen concentrations, Ti-6Al-4V alloys were fabricated from CP Ti with different oxygen concentrations ranging from 1000 ppm to 4000 ppm by adding pure Al and V using a vacuum arc melting furnace. The respective CP Ti and alloy elements (45 g) were placed on a Cu mold and the chamber was evacuated to 5×10^{-3} torr, after which high-purity Ar (99.999 %) gas was introduced until the pressure reached 875 torr prior to melting. The respective arc power and current were 10 KW and 300 A. The specimens after first melting were remelted four 4-times after turning them upside down for homogenization.

For four types of CP Ti and Ti-6Al-4V alloys with different oxygen concentrations, oxygen analyses were performed by means of an inert gas fusion-infrared absorption method using an O-N analyzer (LECO TC-436). To measure the mechanical properties, the Vickers hardness was tested with a 500 g load for 10 s using an Akashi (MVK-E) hardness tester. The average value was selected while excluding the highest and lowest values among 10 measurements of the Vickers hardness. The tensile strength and elongation were assessed with two-ton load at a minimum speed of 1.5 mm using a universal testing machine (RB Model 301). The tensile testing specimens, with a gage length of 10 mm and a thickness of 0.3 mm, were prepared by means of wire electrical discharge machining. To determine the change in the lattice strain and to calculate the *c*/*a* ratio, all specimens were investigated by X-ray diffraction (XRD, Rigaku RTP 300 RC).

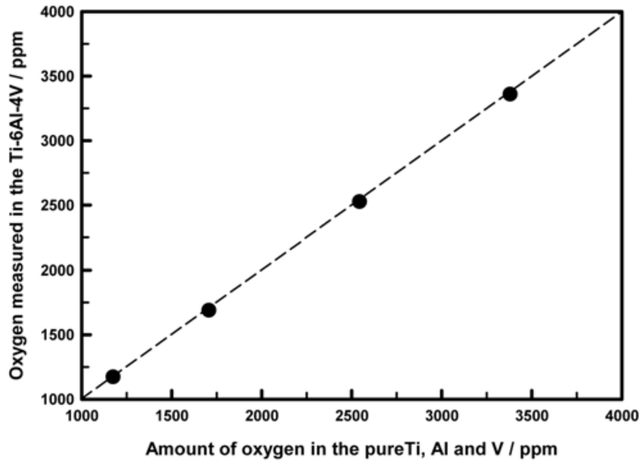

Fig. 1. Comparison of added oxygen concentration and measured oxygen concentration in the Ti-6Al-4V alloys before and after alloying.

3. RESULTS AND DISCUSSION

The measured oxygen concentrations in the CP Ti with grades of G1~G4 were 1310 ppm, 1880 ppm, 2830 ppm, and 3510 ppm, respectively. In addition, the measured oxygen values in the Al and V used here were 20 ppm and 280 ppm, respectively. After alloying Ti-6Al-4V, the measured oxygen values of the Ti-6Al-4V ingots were 1170 ppm, 1690 ppm, 2530 ppm, and 3360 ppm, respectively, the values of which were approximately 90 % of the original oxygen concentration. A graph showing the respective oxygen concentrations and the oxygen measured in the vacuum arc melting furnace melted Ti-6Al-4V was plotted. This is shown in Fig. 1. These results show, that Ti-6Al-4V ingots can be prepared without any oxygen concentration using CP Ti, Al and V by vacuum arc melting. Concerning the effect of interstitial elements on the mechanical properties of CP Ti, Jaffee *et al.* [7] showed that the order of solid solution strengthening is N > O > C. Since the commercial CP Ti and Ti-6Al-4V alloys have wide range of oxygen concentration, in the present study, we focused oxygen effects on the mechanical properties in CP Ti and Ti-6Al-4V alloys.

Figure 2(a) shows the Vickers hardness change of the CP Ti and the Ti-6Al-4V alloys as a function of oxygen concentration. The measured values of the CP Ti ingots were 183 Hv, 219 Hv, 253 Hv, and 298 Hv, respectively. And the values of the Ti-6Al-4V ingots were 325 Hv, 332 Hv, 356 Hv, and 389 Hv, respectively. The Vickers hardness of both the CP Ti and the Ti-6Al-4V alloys almost linearly increased with increasing oxygen concentration. On the other hand, as shown in Fig. 2(a), the slope of the CP Ti was steeper than that of the Ti-6Al-4V alloys. The increase in the Vickers hardness was 115 Hv when the oxygen concentration was ranged from 1310 ppm to 3510 ppm, which means that the hardness increase of 60 % was shown compared to the starting value of the CP Ti. However, in the case of the Ti-6Al-4V alloys, the increase in the Vickers hardness was only 64 Hv with the increase of oxygen concentration from 1170 ppm to 3360 ppm. This value indicates approximately 20 % hardness increase compared to that of the Ti-6Al-4V alloy at 1170 ppm of oxygen concentration. To investigate tensile strength and elongation change of the CP Ti and the Ti-6Al-4V alloys, all the specimens were tested in tension at room temperature. The tensile strength as a function of oxygen

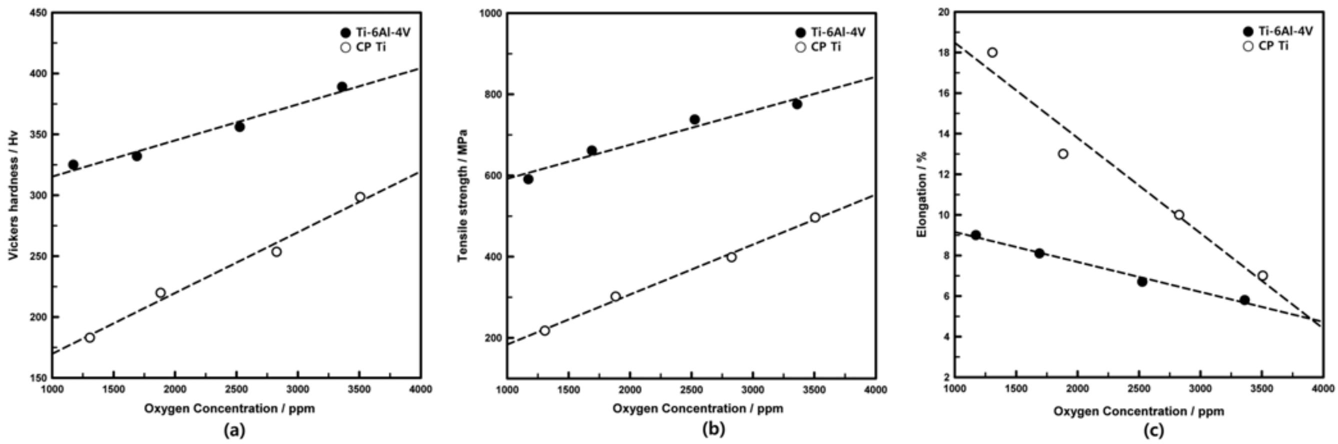

Fig. 2. Variations of (a) Vickers hardness, (b) tensile strength, and (c) elongation of the CP Ti and the Ti-6Al-4V alloys.

concentration in the CP Ti and the Ti-6Al-4V alloys was shown in Fig. 2(b). The measured values in tensile strength of the CP Ti ingots were 217 MPa, 301 MPa, 398 MPa, and 496 MPa, respectively. And the Ti-6Al-4V ingots measured to 590 MPa, 661 MPa, 737 MPa, and 775 MPa, respectively. It was found that the tensile strength of CP Ti and Ti-6Al-4V alloys increased with the increase in oxygen concentrations. Therefore, the trend of result in the tensile strength is very similar to that of the Vickers hardness. The variation of elongation in the CP Ti and the Ti-6Al-4V alloys with different oxygen concentration are shown in Fig. 2(c). The trend of elongation change was different to that of the Vickers hardness and tensile strength. As the oxygen concentration increased, the elongation values of both samples decreased. The measured elongation values of the CP Ti ingots were 18.2 %, 13.1 %, 10.3 % and 7.2 %, respectively and the values of the Ti-6Al-4V ingots were 9.0 %, 8.1 %, 6.7 % and 5.8 %, respectively. The elongation value sharply decreased down to 40 % of the starting value while the oxygen concentration increased from 1310 ppm to 3510 ppm for the CP Ti. However, the variation of elongation for the Ti-6Al-4V alloys was around 36% with the increase of oxygen concentration from 1170 ppm to 3360 ppm. This means that the addition of Al and V to CP Ti reduced the effect of oxygen on the elongation of CP Ti as a function of oxygen concentration.

We found that there is a distinct difference in the oxygen concentration effect on the mechanical properties of CP Ti and Ti-6Al-4V alloys. To explain the difference in the oxygen effect, we investigated the changes in the lattice strain of CP Ti and Ti-6Al-4V alloys with different oxygen concentrations using X-ray diffraction. Figures 3(a) and (b) show the XRD spectra of the CP Ti and the Ti-6Al-4V alloys with different oxygen concentrations, respectively. All of the XRD spectra conform to the hcp structure of Ti without major structural changes. Here, the oxygen concentration increased, the intensity of the major peaks slightly decreased, indicating that oxygen atoms exist between the Ti lattices as an interstitial element. The lattice strain caused by this interstitial solid solution relaxes the crystalline of CP Ti and Ti-6Al-4V alloys. To confirm the effect of the oxygen solid solution on the lattice strain in the CP Ti and the Ti-6Al-4V alloys, the lattice parameters were calculated using a procedure given for the Ti hexagonal system [8]. Figure 4 shows the *c*/*a* ratio calculated for the CP Ti and the Ti-6Al-4V as a function of the oxygen concentration. As shown in Fig. 4, each gradient of the *c*/*a* ratio for the CP Ti and the Ti-6Al-4V alloys is very similar to that from the Vickers hardness and tensile strength results. The increase in the *c*/*a* ratio for both specimens indicates an increase in the solid solution caused by the higher oxygen concentration. Generally, it is known that the *c*/*a* ratio of pure Ti and Ti alloy varies with the content of the interstitial/substitutional element such as oxygen, and an

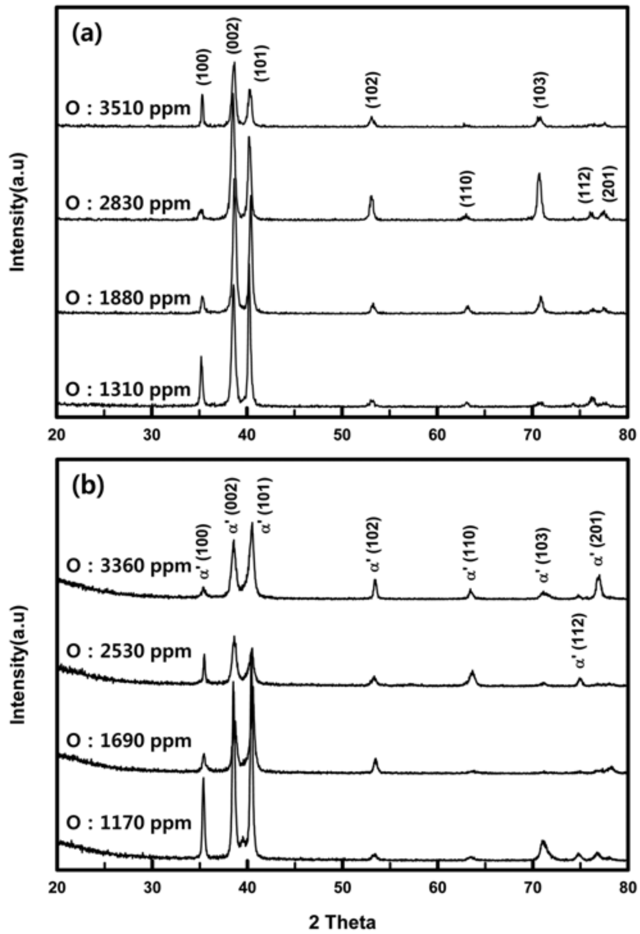

Fig. 3. XRD patterns of (a) the CP Ti and (b) the Ti-6Al-4V alloys.

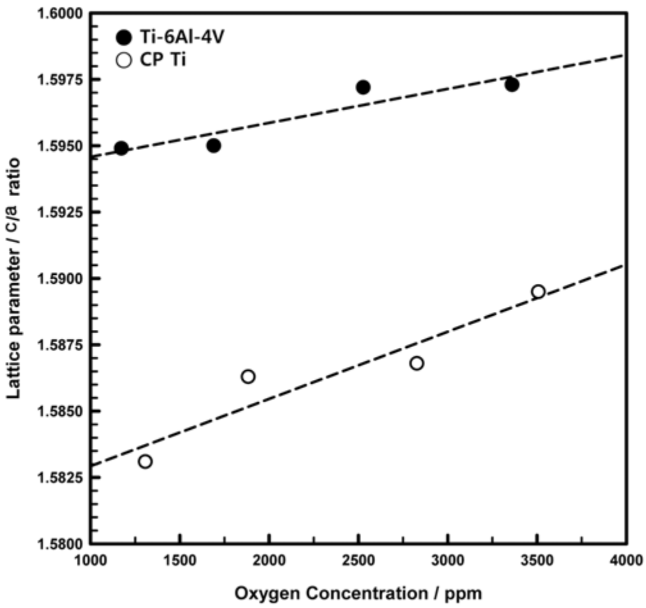

Fig. 4. Variations of the *c*/*a* ratio of the CP Ti and the Ti-6Al-4V alloys.

increase in the *c*/*a* ratio leads to an increase in the hardness and strength due to the restricted number of slip planes in the hcp structure [9]. As shown in Fig. 4, the *c*/*a* ratio for the Ti-6Al-4V alloys is higher than that of the CP Ti with the same oxygen concentration. This may be due to the lattice expansion of the Ti-6Al-4V alloys resulting from the alloying with Al and V. For the Ti-6Al-4V alloys, the lattice strain was already affected by the substitutional element of Al and V during the alloying process, after which the increment in the *c*/*a* ratio of the CP Ti exceeded that of the Ti-6Al-4V alloys. Ouchi *et al.* [10] reported that the effect of the oxygen concentration on the microstructural properties of the Ti-xAl-xV alloy was reduced in comparison with that for CP Ti. The variation in the *c*/*a* ratio, shows that the oxygen concentration has a greater effect on the mechanical properties of CP Ti compared to its effect on the Ti-6Al-4V alloy.

4. CONCLUSION

The effects of oxygen on the mechanical properties and the lattice strain of CP Ti and Ti-6Al-4V alloys were investigated. The Vickers hardness and tensile strength of CP Ti and Ti-6Al-4V alloys increased as the oxygen concentration increased. On the other hand, the elongation of the CP Ti decreased considerably as the oxygen concentration increased, whereas that of the Ti-6Al-4V alloys decreased gradually with an increase in the oxygen concentration. We found that the oxygen concentration has a greater effect on the mechanical properties of CP Ti then it does on the of Ti-6Al-4V alloy. This suggests that the mechanical properties of the Ti-6Al-4V alloy are affected beforehand by a previous lattice expansion that arises during the alloying process with Al and V.

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