Quasi-Static and Dynamic Properties of Ti-4Al-3V-0.6Fe-0.2O Titanium Alloy Plates

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Abstract. This paper aimed to study the quasi-static and dynamic properties of the titanium alloy with nominal composition Ti-4Al-3V-0.6Fe-0.2O. The ingots Ti-4Al-3V-0.6Fe-0.2O alloy were forged into slabs of 32 mm thickness by one heat above $T_{\beta\text{-transus}}$ temperature and one heat below $T_{\beta\text{-transus}}$ temperature, and then rolled into plates of 8 mm thickness by one heat below $T_{\beta\text{-transus}}$ temperature. The quasi-static tensile properties were tested by MTS™ testing system at strain rate of $10^{-3}$ s$^{-1}$. The dynamic compression properties were tested by Split Hopkinson Pressure Bar system at strain rate of 3000±200 s$^{-1}$. The results show that the quasi-static properties of the Ti-4Al-3V-0.6Fe-0.2O plate are comparable to ATI 425™ alloy plate and commercial Ti-6Al-4V plate. The average dynamic flow stress of Ti-4Al-3V-0.6Fe-0.2O plate is comparable to ATI 425™ alloy plate, over 100MPa higher than that of Ti-6Al-4V plate. The maximum strain during homogeneous dynamic plastic deformation of Ti-4Al-3V-0.6Fe-0.2O plate is approximately 15 ~ 20% higher than that of ATI 425™ alloy plate, and is approximately 80% of that of Ti-6Al-4V plate.

1. Introduction

Compared to steel or aluminum alloys, the annual consumption of titanium alloys is smaller due to its higher cost. Reducing the cost of titanium alloys has been urgently demanded in recent years. At present, the technology of low-cost process for titanium sponge has not been realized in industrial scale. Thus, sufficient use of recycled titanium scraps, which can be realized by the technology of electron beam cold hearth melting (EBCHM)[1-2], has been widely regarded as an efficient method of cost reduction. Titanium scraps are usually recycled from leftover bits and pieces of slabs or ingots. As Ti-6Al-4V alloy is the most common and widely used titanium alloy, it is easy to find abundant amount of Ti-6Al-4V scraps. Low-cost Ti-6Al-4V alloy products with recycled titanium scraps addition have already been used in combat vehicles and aircrafts [3]. In titanium scraps exist the impurities such as Fe, O. The content of iron or oxygen in scraps may increase during the process of recycling. Thus, the series of Ti-Al-V-Fe-O alloys, which has the potential for low-cost producing via using scraps with high impurity content, are designed on the base of Ti-6Al-4V alloy.

ATI 425™ titanium alloy, developed by Wah Chang (Oregon, USA), is one of Ti-Al-V-Fe-O alloys with comparable strength and improved formality to Ti-6Al-4V[4]. The nominal chemical composition of ATI 425™ alloy is as 3.5 wt%~4.5 wt% Al, 2.0 wt%~3.0 wt% V, 1.2 wt%~1.8 wt% Fe, 0.20 wt%~0.30 wt% O, with the balance of Ti. ATI 425™ alloy was initially designed for the purpose of ballistic protection, demanding the resistant to dynamic loading. The researches on Ti-6Al-4V showed that the dynamic load-bearing capacity is influenced by hot working and heat treatment[5-7], as well as the content of Al, V, Fe, O elements[8]. In our previous study[9], dynamic properties of ATI 425™ alloy were investigated by hot rolled plate with nominal composition Ti-3.5Al-2.5V-1.5Fe-0.25O, of which the aluminum content reached lower limit. In this paper, Ti-4Al-3V-0.6Fe-0.2O alloy
plates were prepared for the purpose of investigating quasi-static and dynamic properties of ATI 425™ alloy with extensive composition.

2. Experimental
The ingots of Ti-4Al-3V-0.6Fe-0.2O titanium alloy were double VAR-melted with 20 kg in weight, which has a composition of 4.30±0.15 wt% Al, 2.90±0.09 wt% V, 0.58±0.02 wt% Fe, 0.20±0.01 wt% O, 0.012±0.002 wt% C, 0.012±0.002 wt% N, 0.0010 wt% H, with the balance of Ti. The b-transus temperature (T_b-transus) of the ingot was tested as 985±5 °C. The ingots were forged into slabs of 32 mm thickness by one heat at the temperature of 40–50 °C above T_b-transus and one heat at the temperature of 40–50 °C below T_b-transus, and then hot rolled at the temperature of 930 °C into the plates of 8 mm thickness. The as-rolled Ti-4Al-3V-0.6Fe-0.2O plates were respectively heat treated as following: HT1, 750 °C/ 1 hour/ Air cooling; HT2, 930 °C/ 1 hour/ Air cooling; HT3, 940 °C/ 1 hour/ Air cooling; HT4, 960 °C/ 1 hour/ Air cooling.

The quasi-static tensile properties were performed on MTS™ testing system at strain rate of 10^{-3} s^{-1}. Standard specimens for tensile test were 5 mm in diameter and 25 mm in gauge length, with the axis perpendicular to rolling direction of the plate (T-direction). Dynamic compression properties were tested by a SHPB equipment at average strain rate of 2000–3000 s^{-1}. At the strain rate of 2000–3000 s^{-1}, visible damages can be observed on the specimens. Specimens for dynamic test were machined into cylinder shape, with 4 mm in diameter and 4 mm in length and the accuracy were controlled to 0.015 mm. The axis of the dynamic testing specimen was parallel to normal direction of the plates. Both top and bottom surface of the dynamic specimens were grounded to 600♯ sand paper to enhance a smooth contact with the compression platens during tests. The values of average flow stress \( \sigma \), maximum strain \( \varepsilon \) and absorbed energy \( E \) during dynamic homogeneous plastic deformation were calculated via stress-strain curves obtained by SHPB compression testing.

The microstructures of the plates after various heat-treatment were examined by Axiovert 200 MAT optical microscopy (OM). The metallographic specimens were polished and etched by a solution with the volume fraction of 5% HF +10% HNO3+85% H2O at room temperature.

3. Results
The optical microstructures of the Ti-4Al-3V-0.6Fe-0.2O plates after heat treatment HT1~HT4 are shown in Fig. 1 (a)–(d). The microstructure of the plate after conventional annealing treatment HT1 is consisted of elongated \( \alpha \) phase. Bimodal microstructure, consisting of primary \( \alpha \) phase (\( \alpha_p \)) and transformed \( \beta \) phase, can be obtained by heat treatment at elevated annealing temperature as HT2–HT4. The volume fractions of \( \alpha_p \) for HT2, HT3, HT4 plates are 58±3%, 54±3%, 20±3% respectively. It is indicated that the microstructures of Ti-4Al-3V-0.6Fe-0.2O alloy can be controlled as similar types to that of commercial Ti-6Al-4V or ATI 425™ alloys after proper processing of rolling and heat treatment.

The quasi-static tensile properties of Ti-4Al-3V-0.6Fe-0.2O plates are shown in Table.1, which are comparable to commercial Ti-6Al-4V plates or ATI 425™ plates. For commercial Ti-6Al-4V plates in 8mm-thick after HT1 heat treatment, the typical quasi-static properties (in T-direction) are usually tested as 1040 MPa ~ 1070 MPa in ultimate tensile strength, 1015 MPa ~1040 MPa in yield strength, 11.0% ~ 13.0% in elongation and 28% ~ 40% in reduction of area. For ATI 425™ plates in our previous study, that were tested as 1085 MPa ~ 1100 MPa in ultimate tensile strength, 980 MPa ~1065MPa in yield strength, 18.5% ~ 21.0% in elongation and 43% ~ 48% in reduction of area.

Fig.2 shows typical true stress-strain curves of Ti-4Al-3V-0.6Fe-0.2O plates performed in SHPB compression experiment at the strain rate of 2000–3000 s^{-1}. The variation tendency of the curves is similar to that of ATI 425™ plates, but quite different from that of Ti-5Al-3V-0.025Fe-0.044O alloy [12] in our previous study, indicating that Fe element aggravates the effect of softening during dynamic deformation.
Figure 1. Microstructures of Ti-4Al-3V-0.6Fe-0.2O plate after various heat treatment. (a) HT1; (b) HT2; (c) HT3; (d) HT4.

Table 1. Quasi-static tensile properties of Ti-4Al-3V-0.6Fe-0.2O after various heat treatment.

| Heat treatment | Ultimate tensile strength / (MPa) | Yield strength / (MPa) | Elongation / | Reduction of area / |
|----------------|-----------------------------------|------------------------|--------------|---------------------|
| HT1            | 1095±15                           | 1040±10                | 16.0±1.0     | 42±3                |
| HT2            | 1055±15                           | 960±5                  | 17.0±1.0     | 43±2                |
| HT3            | 1040±10                           | 950±10                 | 15.0±1.0     | 40±1                |
| HT4            | 1000±15                           | 900±15                 | 10±1.5       | 25±2                |

Figure 2. Typical true stress-strain curves of Ti-4Al-3V-0.6Fe-0.2O after various heat treatment.
Typical dynamic properties Ti-4Al-3V-0.6Fe-0.2O after various heat treatment are shown in Table 2. The average flow stress $\sigma$, maximum strain $\varepsilon$, and absorbed energy $E$ during homogeneous plastic deformation, were calculated from true stress-strain curves for each specimens with various heat treatment. In our previous study[9,10], typical SHPB compression properties of 8 mm-thick commercial Ti-6Al-4V plates were as $\sigma=1460\pm15$ MPa, $\varepsilon=0.17\pm0.02$, $E=255\pm20$ J/cm$^3$, while that of ATI 425$^{TM}$ plates were as $\sigma=1550\pm30 \sim 1600\pm30$ MPa, $\varepsilon=0.09\pm0.01 \sim 0.13\pm0.01$, $E=150\pm15 \sim 200\pm15$ J/cm$^3$. As a comparison, Ti-4Al-3V-0.6Fe-0.2O plates exhibit comparable dynamic strength to ATI 425$^{TM}$ alloy plate, over 100MPa higher than that of Ti-6Al-4V plate. The maximum strain during homogeneous dynamic plastic deformation of Ti-4Al-3V-0.6Fe-0.2O plate is approximately 80% of that of Ti-6Al-4V plate, and is approximately 15 ~ 20% higher than that of ATI 425$^{TM}$ alloy plate.

Compared Ti-4Al-3V-0.6Fe-0.2O alloy with Ti-6Al-4V alloy, the increase in iron content contributes to the improvement in both quasi-static strength and dynamic strength. Compared Ti-4Al-3V-0.6Fe-0.2O alloy with ATI 425$^{TM}$ alloy, higher aluminum and vanadium content with lower iron content affects slightly on quasi-static strength and dynamic strength, and causes noticeable deterioration in quasi-static plasticity, but leads to enhancement in dynamic plasticity.

### Table 2. Dynamic properties of Ti-4Al-3V-0.6Fe-0.2O after various heat treatment.

| Heat treatment | Average flow stress $\sigma$ (MPa) | Maximum strain during homogeneous plastic deformation $\varepsilon$ | Absorbed energy during homogeneous plastic deformation $E$ (J/cm$^3$) |
|----------------|-----------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| HT1            | 1570±35                           | 0.16±0.01                                                     | 240±20                                                       |
| HT2            | 1540±25                           | 0.16±0.02                                                     | 235±20                                                       |
| HT3            | 1570±30                           | 0.14±0.01                                                     | 215±25                                                       |
| HT4            | 1600±15                           | 0.15±0.01                                                     | 235±15                                                       |

4. Conclusion
Manufactured in similar conditions of rolling and heat treatment, quasi-static properties of Ti-4Al-3V-0.6Fe-0.2O titanium alloy are comparable to the commercial Ti-6Al-4V alloy and ATI 425$^{TM}$ alloy. The average dynamic flow stress of Ti-4Al-3V-0.6Fe-0.2O plate is comparable to ATI 425$^{TM}$ alloy plate, over 100MPa higher than that of Ti-6Al-4V plate. The maximum strain during homogeneous dynamic plastic deformation of Ti-4Al-3V-0.6Fe-0.2O plate is approximately 80% of that of Ti-6Al-4V plate, and is approximately 15 ~ 20% higher than that of ATI 425$^{TM}$ alloy plate.

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