Dynamic Compression Properties of Ti-xV Titanium Alloys

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Abstract. This paper is aimed to study the effects of vanadium on dynamic properties of titanium alloys. A series of Ti-xV alloys, with nominal composition Ti-2V, Ti-4V, Ti-8V, Ti-16V and Ti-32V, were prepared as typical representatives for near $\alpha$, ($\alpha+\beta$), metastable $\beta$, and $\beta$ alloys. The dynamic stress-strain behaviors of Ti-xV alloys were investigated by Split Hopkinson Pressure Bar system at the strain rates of 3000±200 s$.^-1$. After impact, no visible damages can be observed on specimens of Ti-xV alloys except Ti-16V alloy. Except Ti-32V alloy, it can be found obvious strain hardening effect on the other four alloys. Among the five alloys, Ti-16V alloy exhibits the best dynamic strength. Because strain hardening effect disappears in Ti-32V alloy, the dynamic strength of Ti-32V alloy is a little lower than that of Ti-8V alloy when Ti-8V alloy deformed with dynamic strain of 0.23~0.25.

1. Introduction
Titanium and its alloys are important structural material and attractive for a variety of applications in aircrafts and weapons owing to low density, fine mechanical properties, excellent corrosion resistance, and good ballistic performance. When be used in circumstances of collision, impact, penetration and exploding, titanium and its alloys are mainly encountered dynamic loading (strain rate$>10^2$ s$^{-1}$). The combined values of dynamic flow stress, maximum strain during homogeneous plastic deformation, absorbed energy during homogeneous plastic tested by the Split Hopkinson Pressure Bar (SHPB) system were widely accepted to evaluate the dynamic load-bearing capacity for titanium alloys [1-2]. The researches showed that dynamic properties of titanium alloys are dependent on alloying composition and details of microstructure [3-10].

However, most of the studies on dynamic properties focused on commercial alloys or their substitutors, which are composed of both $\alpha$ stabilizer elements and $\beta$ stabilizer elements. To design new alloys with good dynamic load-bearing capacity requires the investigation of the effect of single alloying element, especially $\beta$ stabilizer element. Once $\beta$ stabilizer elements are added in $\alpha$-titanium, microstructure varies remarkably due to the introduction of $\beta$ phase as well as $\alpha/\beta$ phase interfaces, which results in a variation on properties and deformation behavior. Considering vanadium was a most common $\beta$ stabilizer element for titanium, it was adopted in present study. A series of binary Ti-xV alloys were designed, with the addition of vanadium ranging from 2 wt%~32 wt%. One near $\alpha$ alloy, two ($\alpha+\beta$) alloys, one metastable $\beta$ and one stable $\beta$ alloy were prepared to investigate the influence of $\beta$ stabilizer elements on dynamic properties. Considering impurities such as iron and oxygen exhibited non-ignorable influence on dynamic properties[3], binary Ti-xV alloys were prepared by high purity titanium and electrolytic vanadium.

2. Experimental
A series of binary Ti-xV ingots, with nominal composition Ti-2V, Ti-4V, Ti-8V, Ti-16V and Ti-32V, were prepared by multiple non-consumable vacuum arc melting using high purity titanium and...
electrolytic vanadium. The chemical compositions of the alloys are shown in Table 1. The β transus temperatures (T_β-transus) of Ti-2V, Ti-4V, Ti-8V and Ti-16V alloys were measured to be about 1133 K, 1103 K, 1023 K and 973 K, respectively. Ti-32V alloy was totally consists of β phase at room temperature. The ingots of Ti-xV alloys were rolled with a reduction of 60% into plates of 7 mm × 40 mm × 70 mm. In order to obtain microstructures with similar grain size, the plates of Ti-2V, Ti-4V, Ti-8V alloys were annealed as (T_β-transus-20) K/2, 4, 6 hours/Furnace cooling, while the plates of Ti-16V, Ti-32V alloys were heat treated as 720°C, 800°C/1, 1.5 hours/Water Quenching.

Table 1. Chemical composition (in wt.%) of the Ti-xV alloy

| (wt.%) | V  | C  | O   | N   | H   | Fe  | Ti   |
|--------|----|----|-----|-----|-----|-----|------|
| Ti-2V  | 2.09 | 0.012 | 0.077 | 0.0031 | 0.0016 | 0.052 | Bal. |
| Ti-4V  | 3.94 | 0.013 | 0.074 | 0.036 | 0.0016 | 0.022 | Bal. |
| Ti-8V  | 7.86 | 0.013 | 0.058 | 0.003 | 0.0018 | 0.016 | Bal. |
| Ti-16V | 15.54 | 0.01 | 0.025 | 0.003 | 0.001 | 0.025 | Bal. |
| Ti-32V | 31.16 | 0.0053 | 0.028 | 0.0034 | 0.0013 | 0.026 | Bal. |

Dynamic compression properties were tested by a SHPB equipment at average strain rate of 3000±200 s⁻¹. The specification of the impact bar of SHPB system was of φ14.5×200 mm. The pressure of the gas gun of SPHB system was adjusted as about 0.5 MPa. Cylinder specimens were adopted, with 4 mm in diameter and 4 mm in length. The axis of the specimen was parallel to normal direction of the plates. Both top and bottom surface of the dynamic specimens were grounded to 800# sand paper with the purpose of enhancing a smooth contact with the compression platens during tests. The values of average flow stress σ_{average}, Initial flow stress σ_{initial}, maximum flow stress σ_{max}, maximum homogeneous strain before unload or damage, and absorbed energy E during homogeneous plastic deformation were calculated by stress-strain curves obtained by SHPB compression testing.

The microstructures of Ti-xV alloys were examined by an optical microscope (OM) Axiovert 200 MAT. Specimens were polished and etched by a solution with the composition of 5% HF+10% HNO₃+85% H₂O at room temperature.

3. Results

Fig. 1 shows the microstructures of Ti-xV specimens with dynamic true strain about 0.3 during SPHB test. As near α and (α+β) alloys, the microstructures of Ti-2V, Ti-4V, Ti-8V alloys are mainly consisted of equiaxed α phase grains. Twin structures exist in a certain number of α phase grains in Ti-2V, Ti-4V, Ti-8V, as shown in Fig. 1 (a) ~ (c). It also can be found that the twining density declines with the increase of vanadium content from 2 wt% to 8 wt%. It is inferred that the increase of content of β phase with abundant slip systems results in a suppression of twinning but an active dislocation slip mechanism. As a meta-stable β alloy, the microstructure of Ti-16V alloy is consisted of equiaxed β phase grains because no α phase particles are transform when heated above T_β-transus and followed water quenching. A large number of lamellar-like features with certain thickness exist in β grains for Ti-16V alloy, as shown in Fig. 1 (d). The lamellar-like features are determined to be {332}<113> type twinning, which is specific to β titanium alloys[11]. As a stable β alloy, the microstructure of Ti-32V alloy is totally consist of equiaxed β phase grains. No twin structures can be found in grains of Ti-32V, as shown in Fig. 1 (e).

Fig. 2 shows the typical flow stress-strain curves of the plates tested in the SHPB compression experiment at a strain rate of 3000±200 s⁻¹. After impacted by SHPB test, no visible damages can be observed on the specimens of Ti-xV alloys except Ti-16V alloy. Thus, the end of stress-strain curves for Ti-2V, Ti-4V, Ti-8V, and Ti-32V means unload, while the drop of stress-strain curve for Ti-16V means fracture. The stress-strain curves of Ti-2V, Ti-4V, Ti-8V, and Ti-16V show pronounced effect of strain-hardening. However, the stress-strain curve of Ti-32V fluctuates in relative narrow range between linear elastic rise and sudden drop preceding unload, due to the competition between the effects of deformation hardening and thermal softening.
Typical average flow stress $\sigma_{\text{average}}$, initial flow stress $\sigma_{\text{initial}}$, maximum flow stress $\sigma_{\text{max}}$, maximum homogeneous strain before unload or damage, and absorbed energy $E$ during homogeneous plastic deformation, calculated from flow stress-strain curves, were shown in Table 2. The flow stress level rises with vanadium content ranging from 2 wt% to 8 wt% for near $\alpha$ or ($\alpha$+$\beta$) alloys. Compared to Ti-3Al-2.5V alloy or Ti-6Al-4V alloy, the contribution of vanadium to dynamic strength is lower than aluminum. In our previous study [3], typical $\sigma_{\text{average}}$ of Ti-3Al-2.5V tube and Ti-6Al-4V ELI bar were respectively as 850–950MPa and 1200–1300MPa. However, visible damages usually occur in Ti-3Al-2.5V and Ti-6Al-4V ELI specimens when dynamic deformed with the strain value less than 0.23–0.25, which indicates that vanadium enhances dynamic plasticity. Ti-16V meta-stable $\beta$ alloy exhibits the best dynamic strength but the worst dynamic plasticity. However, dynamic strength of Ti-xV alloy was not enhanced as the vanadium content reach to 32 wt%. Because the effect of strain hardening disappears, the dynamic strength of Ti-32V alloy is a little lower than that of Ti-8V alloy when Ti-8V alloy deformed with dynamic strain of 0.23–0.25.
Figure 2. Typical true stress-strain curves of Ti-xV alloys at the strain rates of 3000±200 s⁻¹

|        | Average flow stress $\sigma_{\text{average}}$ (MPa) | Initial flow stress $\sigma_{\text{initial}}$ (MPa) | Maximum flow stress $\sigma_{\text{max}}$ (MPa) | Maximum homogeneous strain before unload or damage $\varepsilon$ | Absorbed energy during homogeneous plastic deformation $E$ (J/cm³) |
|--------|-----------------------------------------------------|---------------------------------------------------|-----------------------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------|
| Ti-2V  | 635±20                                              | 450±20                                            | 765±20                                        | 0.23±0.01                                                                  | 140±20                                                            |
| Ti-4V  | 720±20                                              | 600±20                                            | 820±20                                        | 0.24±0.01                                                                  | 170±20                                                            |
| Ti-8V  | 770±20                                              | 660±20                                            | 865±20                                        | 0.25±0.02                                                                  | 190±15                                                            |
| Ti-16V | 940±30                                              | 860±30                                            | 1060±30                                       | 0.17±0.01(damage)                                                         | 155±10                                                            |
| Ti-32V | 825±20                                              | 825±20                                            | 835±20                                        | 0.15±0.02                                                                  | 120±10                                                            |

4. Conclusion
After impact by Split Hopkinson Pressure Bar system at the strain rates of 3000±200 s⁻¹, no visible damages can be observed on the specimens of Ti-xV alloys except Ti-16V alloy. Except Ti-32V alloy, it can be found that obvious strain hardening effect on the other four alloys. Among the five alloys, Ti-16V alloy exhibits the best dynamic strength. Because strain hardening effect disappears in Ti-32V alloy, the dynamic strength of Ti-32V alloy is a little lower than that of Ti-8V alloy when Ti-8V alloy deformed with dynamic strain of 0.23~0.25.

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