Influence of primary α-phase volume fraction on the mechanical properties of Ti-6Al-4V alloy at different strain rates and temperatures

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Abstract. Bimodal microstructures with primary α-phase volume fractions ranging from 14.3% to 57.1% were gained in Ti-6Al-4V (Ti-64) alloy through annealed in two-phase region at various temperatures below the β-transus point. Then the influence of the primary α-phase volume fraction on the mechanical properties of Ti-64 were studied. The results show that, at room temperature and a strain rate of 10⁻³ s⁻¹, the yield stress decreases but the fracture strain augments with added primary α-phase volume fraction. The equiaxed primary α-phase possesses stronger ability to coordinate plastic deformation, leading to the improvement of the ductile as well as degradation of the strength of Ti-64 with higher primary α-phase volume fraction. As the temperature goes up to 473 K, the quasi-static yield stress and ultimate strength decrease first and then increase with the incremental primary α-phase volume fraction, due to the interaction between the work hardening and the softening caused by the DRX and the growth of the primary α-phase. At room temperature and a strain rate of 3×10³ s⁻¹, the varying pattern of strength with the primary α-phase volume fraction resembles that at a quasi-static strain rate. However, the flow stress significantly increases but the strain-hardening rate decreases compared to those at quasi-static strain rate due to the competition between the strain rate hardening and the thermal softening during dynamic compression process.

1. Introduction
Titanium alloys have been diffusely used in aerospace industry, petrochemical industry and military industry, etc., because of their excellent properties such as good specific strength and outstanding corrosion resistance [1-3]. Ti-6Al-4V alloy (hereafter, Ti-64) is one of the most widely used titanium alloys [4]. Ti-64 is a classic Ti alloy, which consists of hexagonal-close-packed (HCP) α and body-centered-cubic (BCC) β phases [4]. Ti-64 has ~4 wt. % of V, the β-stabilizing element, so that part β phases can be retained at room temperature. Ti-64 can possess various types of microstructures by heat treated under different combination of temperatures, times and cooling-rates [3].

Microstructural characteristics, such as the morphology, size and volume fraction of equiaxed α-phase, α-lamella thickness, prior β-grain size, etc., will intensively influence the mechanical properties...
of Ti-64 [5-8]. Experiments performed by Semiatin and Bieler [5] showed that the change in the peak stress of Ti-64 with the α-lamella thickness during thermal deformation obeys the Hall–Petch relationship. Zhang et al. [6] reported that, compared with the base metal with bimodal microstructure, the electron-beam welded metal of Ti-64 with Widmanstatten microstructure possesses better strength but worse ductility during both quasi-static and dynamic tensile tests. After a scientific research of the data in previous literatures, Wu et al. [7] showed that the high cycle fatigue (HCF) strengths of Ti-64 decline in the order of bimodal, lamellar and equiaxed microstructure. Liu et al. [8, 9] found that microstructure type (bimodal or lamellar) also affects the dynamic fracture behavior of Ti-64 at strain rates higher $10^3$ s$^{-1}$. In addition, the microstructural characteristics also remarkably influence the thermoformability of Ti-64 [10-12]. However, the influence of primary α-phase volume fraction on the mechanical properties of Ti-64 at various strain rates and temperatures is not yet clear.

In the present study, bimodal microstructures with different primary α-phase volume fractions are gained by heat treatments. Then the influence of primary α-phase volume fractions on the mechanical properties of Ti-64 is studied at different strain rates and temperatures. These research results assist to understand the deformation process of Ti-64 alloy.

2. Experiments
The Ti-64 alloy studied in this work was a 30 mm-diameter forging bar stocks. The chemical composition (in wt.%) is Al 5.82, V 3.84, Fe 0.16, O 0.08, C 0.024, H 0.0014, N 0.023, and balanced Ti. The beta-transus temperature $T_\beta$ of this alloy determined by DSC is 1266 K. For obtaining bimodal microstructures with various primary α-phase volume fractions, the forging bars were annealed at 1246, 1226 and 1206 K (20, 40 and 60 K below $T_\beta$), respectively, for 60 min followed by air cooling (AC). Then these two-phase region annealed alloys were annealed again at 873 K for 2 h followed by AC to stabilize the microstructure and release the internal stress produced during the solution process.

Some cylinders ($\Phi 4 \times 8$ mm or $\Phi 4 \times 4$ mm) were cut from the center of the heat-treated alloy bars for quasi-static and dynamic compression experiments, respectively. Quasi-static compression were conducted at both room and high (473 K) temperatures under a strain rate of 0.001 /s using an MTS 810 hydraulic servo machine. Compression were sostenuto proceeded until the samples broke. High temperature compression tests were performed in a high-temperature environmental chamber. Specimens were keep for 2 min at 473 K before tests. Dynamic compression tests were conducted at room temperature under a strain rate of about $3 \times 10^3$ s$^{-1}$ using a split Hopkinson pressure bar (SHPB) apparatus. More detailed introductions of the SHPB experiment could be acquired in Ref. [13].

The microstructural features of the heat-treated materials were carefully observed using Optical microscope (OM). Samples for OM researches were prepared through electrolytic polishing in a solution of 95% CH$_3$COOH + 5% HClO$_4$, followed by etching in a solution of 2% hydrofluoric acid + 10% nitric acid + 88% deionized water at room temperature. The metallographic features of Ti-64 after heat treatment were observed utilizing a ZEISS Axio Observer A1m OM.

3. Results and discussion

3.1. Microstructural features
Figure 1 presents the optical microstructures of Ti-64 after annealed at different temperatures below $T_\beta$. The normal of the observation surface is perpendicular to the axis of the forging bar. The microstructures of the heat-treated Ti-64 are all composed of the mixture of equiaxed primary α and transformed β. However, the volume fraction of primary α-phase is significantly distinct in this alloy annealed at different temperatures. The quantity of the primary α increases but the volume of the transformed β drops with decreased annealing temperature. When the annealing temperature is below 1246 K, the equiaxed primary α-phase tends to merge with each other and form long grains. The mean grain diameter of the equiaxed primary α-phase (long grains are not counted) is about 8.44±0.36 μm, 7.06±0.40 μm and 6.16±0.25 μm, respectively, and slightly reduces with decreased annealing temperature.
Figure 1. Optical micrographs of Ti-64 alloy annealed in α+β region at (a) 1246 K, (b) 1226 K and (c) 1206 K.

According to the principle of stereology, the volume fraction is equal to the area fraction when using OM images for microstructural characteristics measurement [14]. Hence, the area fraction of the primary α phase is regarded as its volume fraction in the present study. To obtain the precise volume fraction of primary α-phase generated during annealing at different temperatures below $T_β$, statistics were performed over 15 OM photographs. The statistical method used is described elsewhere [15]. The result reveals that the primary α phase volume fraction of Ti-64 annealed at temperatures 20, 40 and 60 K below $T_β$ are 14.34(±1.63)%, 38.16(±1.76)% and 57.06(±2.15)%, respectively. The closer to $T_β$ the annealing temperature is, the greater the undercooling is. The transformed β (martensitic structure) is easier to form during cooling procedure. Consequently, the volume fraction of the primary α declines but that of the transformed β increases with the incremental annealing temperature.

3.2. Mechanical properties

3.2.1. Under quasi-static strain rate and room temperature. Figure 2 shows the stress–strain curves and strength change of Ti-64 with various primary α-phase volume fraction compressed at room temperature and a strain rate of 0.001 /s. As presented in Fig. 2(a), the flow stress declines with augmented primary α-phase volume fraction, although the tendency of the curves is analogical despite the volume fraction of primary α-phase. The strain hardening rate (SHR) of Ti-64 scarcely varies as the plastic strain continues, suggesting that the primary α-phase volume fraction does not affect the SHR of this alloy. On the other side, the fracture strain significantly augments as the primary α-phase volume fraction exceeds about 15%, implying the primary α-phase is good for the plasticity of Ti-64
alloy. The fracture strain can be considered as the largest strain which the sample is able to sustain before it breaks.

**Figure 2.** (a) Quasi-static compressive stress–strain curves of Ti-64 with various primary α-phase volume fraction at room temperature and (b) the corresponding yield stress and ultimate strength vs. the primary α-phase volume fraction.

Figure 2(b) presents the yield stress and ultimate strength as a function of primary α-phase volume fraction of Ti-64 at room temperature. The yield stress of Ti-64 decreases with the incremental primary α-phase volume fraction. The difference in yield stress of Ti-64 with primary α-phase volume fraction increasing from 14.34% to 57.06% is about 57 MPa. The average size of the equiaxed primary α-phases is evidently larger than that of the needlelike α-phases in transformed β (see Figure 1). It means that dislocations in primary α-phase are able to move longer distances, which avoids serious pile-up of dislocations. Namely, the primary α-phase possesses stronger ability to coordinate plastic deformation. Therefore, Ti-64 with higher primary α-phase volume fraction displays lower flow stress and yield stress (lower deformation resistance) but higher fracture strain during compression process. On the other hand, the ultimate strength of this alloy augment only slightly with the incremental primary α-phase volume fraction, suggesting that the proliferation of defects reaches saturation as the plastic deformation proceeds.

3.2.2. Under quasi-static strain rate and high temperature. Figure 3 displays the compression stress–strain curves and strength change of Ti-64 with various primary α-phase volume fraction loaded under quasi-static strain rate and elevated temperature conditions. When the test temperature attains 473 K (Fig. 3(a)), the material reveals significant thermal softening effect. That is to say, the flow stress declines as the plastic strain augments, i.e. Ti-64 acts out a negative SHR when it is compressed at elevated temperature. The fracture strain augments with the incremental primary α-phase volume fraction as well. However, the increment of fracture strain is more uniform (Compared with Figure 2(a)). This indicates that deformation at high temperatures helps to improve the ductile of Ti-64 with a relatively lower primary α-phase volume fraction.

A more interesting phenomenon is that the quasi-static compression yield stress and ultimate strength decrease first and then increase with the incremental primary α-phase volume fraction at 473 K, as shown in Figure 3(b). However, the degree of decline in yield stress is less than that in ultimate strength as the volume fraction of the primary α-phase augments from 14.34% to 38.16%. This result suggests that the thermal softening resistance of Ti-64 decreases first and then increases with the incremental primary α-phase volume fraction. Under high temperature, the deformation behavior of Ti-64 is determined by the interaction between the work hardening and the softening caused by the heat transferred by plastic work and the microstructure evolution such as the nucleation and growth of dynamic recrystallization (DRX) grains and/or dynamic spheroidization [16, 17]. Dislocations are likely to block in transformed β, leading to higher distortion energy stored up in these regions. The
distortion energy known as a driving force can facilitate the nucleation and growth processes of DRX. Hence, DRX grains prefer to nucleate in transformed β. On the other hand, the growth of those primary α-phases also results in the softening effect of Ti-64 deformed at elevated temperature. The larger number (volume fraction) of equiaxed α means smaller growing spaces for this phase, which suppresses the excessive growth of the primary α-phase. Therefore, the Ti-64 with the least transformed β volume fraction but the most primary α-phase volume fraction (57.06%) has the greatest yield stress than the other two. In Ti-64 with the primary α-phase volume fraction of 38.16%, there are enough transformed β regions for the nucleation of DRX grains and enough growing spaces for the growth of the primary α-phase, leading to the lowest yield stress and ultimate strength of the three. However, the greatest ultimate strength of Ti-64 with the primary α-phase volume fraction of 14.34% maybe implies that the strength reduction caused by DRX is weaker than that caused by the growth of the primary α-phase.

Figure 3. (a) Quasi-static compressive stress–strain curves of Ti-64 with various primary α-phase volume fraction at 473 K and (b) the corresponding yield stress and ultimate strength vs. the volume fraction of primary α-phase.

3.2.3. Under dynamic strain rate and room temperature. Figure 4 presents the compressive stress–strain curves and strength change of this alloy with various primary α-phase volume fraction obtained at room temperature and a strain-rate of ~3×10³ s⁻¹. Compared to the deformation behavior at quasi-static strain rate (Fig. 2), the flow stress of materials at dynamic strain-rate significantly increases, although the SHR drops due to the thermal softening effect. More dislocations produce under higher strain rate loading conditions [13]. Hence, the tangling and piling-up of dislocations are more likely to occur under dynamic loading conditions, leading to a higher strength level of Ti-64. On the other hand, the dynamic loading process is believed to occur under adiabatic thermodynamic conditions. Therefore, the heat loss rate is less than the heat generation rate when the metal deforms under high strain-rate conditions, resulting in the temperature rise of the metal. The unremitting temperature rise brings about the synchronous declining of the flow stress [18]. Thus, the SHR decreases during compression at high strain-rates.

The elastic deformation section (yield stress) cannot be accurately obtained using the SHPB apparatus [19]. Additionally, the flow stress of Ti-64 with different primary α-phase volume fractions hardly changes with the strain. Hence, we use the average flow stress instead of the yield stress to show the change in alloy properties with the volume fraction of primary α-phase. The average flow stress (σav.) can be defined as [19]:

\[ σ_{av.} = \frac{\int \sigma(\varepsilon) d\varepsilon}{\varepsilon} \] (1)

The variation of the average flow stress with the volume fraction of primary α-phase is presented in Fig. 4(b). One can find that the average flow stress of Ti-64 at 3×10³ s⁻¹ declines with the incremental
primary α-phase volume fraction as well and has an analogous variation trend compared with the yield stress at quasi-static strain rate (Fig. 2(b)). Finally, the fracture strain of Ti-64 at 3000 s\(^{-1}\) is somewhat lower than that at 10\(^{-3}\) s\(^{-1}\) due to the more serious dislocation pile-up during the dynamic compression process.

![Graph](image)

**Figure 4.** (a) Dynamic compressive stress–strain curves and (b) average flow stress vs. the primary α-phase volume fraction of Ti-64 with bimodal microstructure obtained at room temperature.

### 4. Conclusions

Annealing treatments in the two-phase (α+β) region were performed on Ti-64 to gain the bimodal microstructures with various primary α-phase volume fractions. Then, the influence of the primary α-phase volume fraction on the mechanical properties of Ti-64 was carefully studied through compression tests carried out at different strain-rates and temperatures. The major conclusions are as follows:

1. The primary α-phase volume fraction of 14.34%, 38.16% and 57.06% are obtained in Ti-64 through annealing treatment at 20, 40 and 60 K below \(T_β\), respectively.

2. Under room temperature and a strain rate of 0.001/s, the yield stress declines but the fracture strain augments in Ti-64 with the incremental volume fraction of the primary α-phase. The primary α-phase possesses stronger ability to coordinate plastic deformation, leading to the enhancement of the ductile but the decline of the strength of this alloy with higher primary α-phase volume fraction.

3. Under high-temperature and a strain rate of 0.001/s, the yield stress and ultimate strength decrease first and then increase with the incremental primary α-phase volume fraction, due to the interaction between the strain hardening and the softening caused by the DRX and the growth of the primary α-phase.

4. Under room temperature and a strain rate of 3×10\(^3\) s\(^{-1}\), the varying pattern of strength with the primary α-phase volume fraction is similar to that at a quasi-static strain rate. However, the flow stress significantly increases but the SHR decreases compared with those at quasi-static strain rate due to the interaction among the strain hardening, the strain rate hardening and the thermal softening during dynamic compression process.

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