Hot deformation behavior and microstructure evolution of Ti$_2$AlNb-based alloy in $\alpha_2$+B2 phase region

Feng Zhou, Kelu Wang, Xin Li, Xuhuai Chen and Peng Wan

School of Aeronautical Manufacturing Engineering, Nanchang Hang Kong University, Nanchang 330063, China
E-mail:929399962@qq.com; Tel:+132-0709-0876

Abstract. The hot deformation behavior of Ti-22Al-24Nb alloy at temperatures of 900–1050°C and a strain rate of 0.01–10s$^{-1}$ as well as the microstructure evolution of the $\alpha_2$+B2 phase region were investigated by a Gleeble-3500 thermal simulation tester. The influence of strain rate and deformed temperature on the hot deformation of microstructure and the flow stress curve characteristics of the alloy were analyzed. The results show that the strain rate and deformed temperature have a great influence on the flow stress of Ti-22Al-24Nb alloy. When the strain rate is 1.0s$^{-1}$, the peak stress increases gradually with the decrease of deformed temperature, and the deformed temperature is 930°C. The peak stress decreases as the strain rate decreases, and the flow stress curve of the alloy has the characteristics of stress peak, flow softening, and steady-state flow. Deformed temperature and strain rate have a great influence on the $\alpha_2$+B2 phase region. When deformed at high strain rates ($\dot{\varepsilon} \geq 1.0s^{-1}$), the microstructure of the alloy is prone to local plastic flow and adiabatic shear. When the deformation was carried out at low strain rate ($\dot{\varepsilon} \leq 0.1s^{-1}$), the local plastic flow and adiabatic shear characteristics did not appear in the alloy structure. With the increase of deformed temperature, the dynamic recrystallization possibility increased.

1. Introduction

Ti$_2$AlNb-based alloys are mainly intermetallic compounds based on orthogonal ordered structures O phase, which has strong oxidation resistance, high specific strength at high temperature and creep resistance, and is considered as an ideal light-density high-temperature structural material that contributes to the improvement of the structural quality of the aerospace aircraft engine and the performance improvement thereof [1-3]. However, Ti$_2$AlNb-based alloys are hardly deformable materials, and their mechanical properties and microstructure are sensitive to hot-working process parameters. The traditional hot-forming process has a long trial production cycle, and it is difficult to obtain products with stable performance and consistency during the forming process, severely limits the industrial application of Ti$_2$AlNb-based alloys [4-6]. In this regard, it is necessary to study the influencing factors of high temperature deformation behavior and microstructure of Ti$_2$AlNb-based alloys.

In this study, the isothermal constant strain thermo compression test of Ti-22Al-24Nb (atomic fraction, %) alloy was conducted on a Gleeble-3500 thermal simulation tester. The high temperature flow stress curve characteristics of the alloy were studied, and the influence of strain rate and deformed temperature on the microstructure evolution of hot deformation is analyzed, which provides important theoretical guidance for the thermoforming process control of Ti$_2$AlNb-based alloys.
2. Materials and Methods
The experimental material is Ti$_2$AlNb-based alloy with the nominal composition of Ti-22Al-24Nb, and its chemical composition (mass fraction/%) was: 10.6Al, 41.2Nb, 0.88 Mo, 0.07Si, 0.047Fe, balance Ti. Isothermal constant strain rate compression experiments are performed on a Gleeble-3500 thermal simulator with deformed temperatures of 900, 930, 960, 990, 1020 and 1050°C, and strain rates of 0.01, 0.1, 1.0 and 10s$^{-1}$. The high reduction is 60%, and the corresponding true strain is 0.92. After heating at 5°C/s to the set deformed temperature, it is kept for 300s. In order to make the internal temperature of the sample uniform, the water is cooled immediately after compression. Using the line cutting method, the deformed samples are cut in half along the axial direction and metallographic specimens are prepared. The microstructure are observed on an XJP-6A metallographic microscope after grinding-polishing-etching. Corrosives used were HF+HNO$_3$+H$_2$O in a volumetric ratio of 1:3:7 and HF+H$_2$O$_2$+H$_2$O mixed etchant in a ratio of 2:5:100. After half-sectioning and preparing a metallographic specimen and then observing by OM and SEM (Fig.1), the microstructure of the sampled material is (α$_2$+O+B2) three-phase structure with coarse B2 phase grains and distribution respectively. The equiaxed grain α$_2$ phase on the B2 phase and the O phase in the shape of a dark gray, smaller slat.

![Figure 1.](image-url) Original microstructure of Ti$_2$AlNb-based alloy

3. Results
3.1 Flow Stress Analysis
Metal materials in the process of thermal deformation due to work hardening, dynamic recovery softening and dynamic recrystallization softening and other physical mechanisms, resulting in high temperature flow stress behavior of the material is extremely complex. Fig. 2 shows the true stress-strain curves for Ti$_2$AlNb-based alloys at high temperatures. It can be seen that the overall high temperature flow stress curve of the alloy changes: the flow stress is more sensitive to the effect of deformed temperature and strain rate. When the strain rate is 1.0s$^{-1}$, the peak stress increases gradually with the decrease of the deformed temperature. When the deformed temperature is 930°C, the peak stress gradually decreases with the decrease of the strain rate. In the initial stage of deformation, the flow stress increases rapidly with the increase of strain, and this stage is dominated by strain hardening. With the continuation of the compression deformation, the softening effect is gradually strengthened and the slope of the curve is getting smaller and smaller until the effect of the softening effect and the work hardening effect are almost equal, and the flow stress peaks. As the deformation continues, the curve will show two distinct features: one is that the softening effect is further enhanced, and the curve shows that the flow stress continues to decrease until it stabilizes. The other is that after the flow stress peaks, it shows the steady-state flow characteristics. the peak stress and steady-state stress are not much different. This phenomenon tends to occur at higher temperatures and lower strain rate conditions. It may be that due to the high temperature and low strain rate, the softening effect of the material reaches a certain saturation value when the peak strain is reached. In the subsequent deformation process, the softening effect and the hardening effect are always in a dynamic equilibrium and the flow stress does not change much. The essence of deformation of the alloy in this state is the
proliferation of dislocations and the mutual cancellation between dislocations due to the interaction and the dynamic equilibrium after recombination [7-10].

Figure 2. Stress and strain curves under different thermal deformation conditions

3.2 Effect of Strain Rate on Microstructure of Ti2AlNb-Based Alloy

Fig. 3 shows the thermal deformation structure of Ti-22Al-24Nb alloy at different strain rates at a deformed temperature of 960°C ($\alpha_2$+B2 two-phase zone temperature). As can be seen from Fig. 3, at the strain rate of 0.01s$^{-1}$, most of the $\alpha_2$ phase in the alloy is dispersed on the B2 grain, and a small part is attached to the B2 grain boundary. At the strain rate of 0.1s$^{-1}$, the $\alpha_2$ phase decreases and the grain boundary is blurred. From Fig. 3(c), it can be seen that at the strain rate of 1.0s$^{-1}$, the grain boundary is kinked and fractured, and local plastic flow instability phenomenon occurs. When the strain rate reaches 10s$^{-1}$, the fine $\alpha_2$ phase is dispersed on the B2 phase matrix, almost all of the grain boundaries break and disappear, and a large area of plastic flow instability occurs, as shown in Fig. 3(d).

Figure 3. Microstructure at different strain rates at 960°C
3.3 Effect of Deformed Temperature on Microstructure of Ti₂AlNb-Based Alloy

3.3.1 Low Strain Rate
Fig. 4 shows the microstructure of Ti-22Al-24Nb alloy at different deformed temperatures with 0.1s⁻¹ strain rate. From Fig. 4(a) and (b), it can be seen that at the deformed temperatures of 900 and 960°C, no new crystallites were observed and there was no significant difference in microstructure. When the deformed temperature is 990°C, there are obvious dynamic recrystallization grains at the B2 phase at the trinary grain boundary, and the B2 phase grain boundary is straight and clear. The fine α₂ phase is concentrated in the B2 phase grain.

![Microstructures of different deformed temperatures at the strain rate of 0.1s⁻¹](a)T=900°C  (b)T=960°C  (c)T=990°C

**Figure 4.** The Microstructures of different deformed temperatures at the strain rate of 0.1s⁻¹

3.3.2 High Strain Rate
Fig. 5 shows the microstructure of Ti-22Al-24Nb alloy at different deformed temperatures with 10s⁻¹ strain rate. It can be seen from Fig. 5 that at the deformed temperature of 900°C, the grain boundary is blurred and almost completely disappears, and obvious adiabatic shearing phenomenon occurs. Under the deformed temperature of 1020°C, the grain boundary is obvious, the grain of B2 phase is obviously elongated in the vertical compression direction, and the α₂ phase particles are gathered and arranged in parallel and perpendicular to the compression direction (as shown in the direction of the arrow in Figure 6).

![Microstructures of different deformed temperatures at the strain rate of 10s⁻¹](a)T=900°C  (b)T=1020°C

**Figure 5.** The Microstructures of different deformed temperatures at the strain rate of 10s⁻¹
4. Discussion
When thermal deformation occurs in the α2+B2 phase region, the strain rate has a great influence on the microstructure of Ti2AlNb. At the low strain rate (\(\dot{\varepsilon} \leq 0.1\text{s}^{-1}\)), no local plastic flow occurs in the hot deformed microstructure. However, the local plastic flow instability at high strain rate (\(\dot{\varepsilon} \geq 1.0\text{s}^{-1}\)) is significant. The occurrence of local plastic flow is related to the low thermal conductivity of titanium alloys, it will produce obvious thermal effects during the deformation process, especially under the condition of low temperature and high strain rate, the adiabatic temperature rise effect of the tissue is likely to occur [11,12]. Moreover, when the strain rate continues to increase to 10s\(^{-1}\), the deformation time decreases accordingly, and the thermal softening effect caused by the local adiabatic temperature rise is far more than the plastic strain hardening, resulting in a highly localized deformation of the material.

The literature [13,14] shows that for Ti2AlNb-based alloys with high dislocation energy, the dynamic recrystallization is mainly affected by the grain boundary mobility, and increasing the temperature or decreasing the strain rate can promote the grain boundary migration speed, which shows that the grain boundaries pass through continuous bowel precipitation and lead to the occurrence of dynamic recrystallization, so at low strain rates, dynamic recrystallization is more likely to occur as the temperature of deformation increases. At high strain rates, when the deformed temperature is 900°C, the phase transition temperature of B2 is not reached at 1070°C. Therefore, the adiabatic shear band is mainly characterized by a deformed shear band characterized by severe grain elongation and fracture, rather than a phase change band that is characterized by phase change [15].

5. Conclusions
(1) The effect of flow stress on the deformed temperature and strain rate is sensitive. When the strain rate is 1.0s\(^{-1}\), the peak stress increases gradually with the decrease of the deformed temperature. When the deformed temperature is 930°C, the peak stress gradually decreases with the decrease of the strain rate, and the flow stress curve has the characteristics of stress peak, flow softening, and steady-state flow.

(2) The strain rate and deformed temperature have a significant effect on the microstructure of Ti-22Al-24Nb alloy. When the deformation is performed at a high strain rate (\(\dot{\varepsilon} \leq 1.0\text{s}^{-1}\)) in the α2+B2 phase region, the microstructure of the alloy is prone to local plastic flow and adiabatic shear. When the deformation was carried out at low strain rate (\(\dot{\varepsilon} \leq 0.1\text{s}^{-1}\)), the local plastic flow and adiabatic shearing characteristics did not appear in the alloy structure. With the increase of deformed temperature, the dynamic recrystallization easily occurred in the alloy.

Acknowledgments
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