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Microstructure and high temperature mechanical properties of powder metallurgical Ti-45Al-7Nb-0.3W alloy sheets

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ABSTRACT

The microstructure, high temperature mechanical properties and deformation mechanism of powder metallurgical (PM) Ti-45Al-7Nb-0.3W (at.%) alloy sheets were investigated by X-ray diffraction (XRD), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The tensile test results showed excellent high temperature mechanical properties with a yield stress (YS) of 670 MPa and an ultimate tensile stress (UTS) of 874 MPa at 700 °C and displayed an anomalous strengthening effect, which could be explained by the pinning mechanism of dislocation locks. In addition, the brittle-ductile transition temperature (BDTT) was found at between 800 °C and 850 °C. When deformed below BDTT, high density of dislocations and mechanical twins were observed in the microstructures. However, with increasing deformation temperature above BDTT, kinking of α_2/γ lamellar colonies and dynamic recrystallization also occurred. It was noteworthy that the as-rolled sheets displayed superplastic behaviors at 950 °C with initial strain rates of 1×10^{-4} s^{-1} and 5×10^{-5} s^{-1}. At the same time, severe dynamic recrystallization took place and the grain boundary sliding was improved by β phase, which resulted in an elongation of 243% at the strain rate of 5×10^{-5} s^{-1}.

1. Introduction

TiAl based alloys are considered highly promising high temperature structural materials as a substitute for nickel based alloys because of their attractive properties such as low density, good creep resistance and good high temperature strength etc. [1–4]. TiAl sheets are extremely promising in aerospace applications, including turbine blades, nozzles for helicopters, and back structures for scramjets etc. [5,6].

The high temperature mechanical properties are key performance indexes of TiAl based alloys and there is a continuing need for improving them in order to make those alloys an attractive alternative for conventional nickel based alloys [7,8]. So far, considerable efforts have been devoted to investigating the high temperature mechanical properties of TiAl based alloys. For example, high Nb containing TiAl alloys have been widely studied recently [9–11]. Compared with conventional TiAl alloys, high Nb containing TiAl alloys display remarkably increased mechanical strength from room temperature to 800 °C, which is ascribed to the solution hardening of Nb and microstructural refinement [12,13]. J.D.H. Paul et al. [14] found that Ti-45Al-10Nb alloys and Ti-45Al-5Nb alloys had flow stress values of over 800 MPa at room temperature and over 500 MPa at 900 °C in compression process. In comparison to a conventional Ti-47Al-2Cr-0.2Si alloy, they showed a considerable increase in strength. Nevertheless, the high addition of Nb may bring some problems as well, such as poor hot deformability and low room temperature ductility [12,15]. Thus, more studies on high Nb containing TiAl alloys should be carried out.

It is generally known that the deformation behavior of TiAl based alloys is very complicated because the microstructure of TiAl based alloys usually consists of multiple phases and structures which result in different deformabilities [16,17]. Therefore, there are numerous mechanisms associated with high temperature properties working simultaneously and synergistically during the deformation [7]. Y.W. Kim et al. developed Ti-45Al-5Nb sheets by pack-rolling through ingot metallurgical (IM) process. And they found that the sheets were strengthened by unstable structures, as well as grain-boundary strengthening and γ phase solution strengthening [18].

Up to now, many studies have been performed on TiAl alloy. And in our previous work, powder metallurgical TiAl sheets have already been produced by hot pack-rolling [19,20]. However, microstructure and high temperature mechanical properties of hot pack-rolled high Nb containing PM TiAl sheets need to be further studied.

In this work, the PM Ti-45Al-7Nb-0.3W (at.%) alloy sheets were fabricated by hot pack-rolling. Tensile tests under different conditions were conducted to investigate the microstructure and high temperature mechanical properties of TiAl sheets. Besides, high temperature deformation mechanism and superplastic deformation behaviors at 950 °C were also analyzed in detail.

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2. Experimental procedures

The alloy with nominal composition of Ti-45Al-7Nb-0.3W (at.%) was prepared by powder metallurgy. Plates measuring 50 × 40 × 8 mm^3 were machined from the hot isostatic pressed billet by electric-discharge machining. Then they were encapsulated in 1.5 mm thick pure Ti cans. The specimens were hot rolled on a hot mill with roller dimension of Φ180 mm × 320 mm. And the rollers were preheated at 250–300 °C. After heating to the rolling temperature of 1270 °C and holding for 60 min, TiAl sheets were hot pack-rolled with rolling speed of 40 mm/s and a reduction of 10% per pass. And the sheets were held for 5–8 min between each two rolling pass. After rolling, 4 mm thick sheets were obtained and they were then treated at 900 °C for 1 h followed by air cooling.

Flat tensile test specimens with a gauge section of 8 mm × 3.4 mm × 2.8 mm were cut in rolling direction from the sheets. High temperature tensile tests at different temperatures ranging from room temperature (20 °C) to 950 °C were conducted on an Instron 3369 universal test machine in air with an initial strain rate of $1 \times 10^{-3}\ s^{-1}$. Superplastic deformation behaviors at 950 °C with initial strain rates of $1 \times 10^{-4}\ s^{-1}$ and $5 \times 10^{-5}\ s^{-1}$ were also investigated. All specimens were held at test temperature for 10 min before testing. Once the tensile specimens broke, they were treated by forced air cooling. So the state of high temperature in the specimens could be kept. For each condition, at least three tests were performed and average values were reported.

The grain size of γ phase and α_2/γ lamellae was calculated by a software Image-Pro Plus6.0. The phase composition was determined using Cu K_α radiation on a D/Max 2500 X-ray diffractometer. And the deformed microstructures and fracture surfaces of the tensile specimens were analyzed using a Sirion200 scanning electron microscope (SEM). TEM foils were prepared by mechanical polishing and twin-jet electropolishing using a solution of 6% perchloric acid + 34% butanol + 60% methanol at −20 °C and 25 V, and then observed in a Tecnai $G^2$20 microscope operating at 200 kV.

3. Results

3.1. Microstructure of the sheets

The XRD pattern and SEM backscattered electron (BSE) image of the as-rolled PM Ti-45Al-7Nb-0.3W (at.%) alloy sheets are presented in Fig. 1. As is shown in Fig. 1 (a), the microstructure of the sheets is mainly composed of γ phase, α_2 phase and a small amount of β phase. The SEM image reveals that the sheets show a duplex microstructure with a mean grain size of about 8 μm (Fig. 1 (b)). Meanwhile, the β phase is distributed at the grain boundaries of γ phase and α_2/γ lamellar colonies as can be seen from the picture.

3.2. High temperature mechanical properties

The tensile mechanical properties of the as-rolled PM Ti-45Al-7Nb-0.3W (at.%) alloy sheets with an initial strain rate of $1 \times 10^{-3}\ s^{-1}$ are presented in Fig. 2. As shown, the variation patterns of yield stress (YS), ultimate tensile stress (UTS) and elongation can be concluded as follows. First, at room temperature, the YS, UTS and elongation of the sheets are 582 MPa, 621 MPa and 2%, respectively. They all increase at elevated temperature. However, the YS and UTS drop sharply with the increasing temperature above 700 °C after exhibiting peak values of 670 MPa and 874 MPa. On the other hand, the elongation of the alloy only reaches to 7.2% at 800 °C, but it rapidly increases to 58.1% at 850 °C, which indicates that the brittle-ductile transition temperature (BDTT) of the sheets is between 800 °C and 850 °C. Eventually, at the temperature of 950 °C, the YS and UTS drop to 307 MPa and 402 MPa, while the elongation value increases to 95%.

Fig.3 shows the fracture surfaces of the tensile test specimens tested at room temperature (20 °C), 700 °C, 800 °C, 850 °C, 950 °C, respectively, with an initial strain rate of $1 \times 10^{-3}\ s^{-1}$. It can be seen that the specimens all exhibit brittle fracture modes at the temperature range of 20 °C–800 °C and the fracture modes are characterized by both the γ phase and α_2/γ lamellar colonies. A predominant mode of transgranular fracture with many cleavage planes is observed in Fig.3 (a). While Fig.3 (b) and (d) exhibit delamination along α_2/γ lamellar colonies and translamellar cleavage. Intergranular fracture is also observed in Fig.3 (c), which refers to the fracture mode of large γ grains. This is because large deformation takes place at the grain boundaries, then microcracks initiate and propagate along the grain boundaries due to the high stress concentration [20]. Above 850 °C, the specimens exhibit a typical ductile fracture mode. Many dimples can be clearly seen in Fig.3 (e) and (f) and the fracture surfaces are quite severely oxidized, which results in the formation of oxide modules on the surfaces.

3.3. High temperature deformation microstructures

Fig. 4 shows the SEM BSE images of deformed microstructures after tensile tests at 20 °C, 800 °C, 850 °C and 950 °C, respectively. Compared with the microstructure of as-rolled sheets in Fig. 1 (b), there is not any significant change of microstructures after deformation at 20 °C and 800 °C, as depicted in Fig. 4 (a) and (b). However, when the tensile test temperature increases to 850 °C or even higher, to 950 °C (Fig. 4 (c) and (d)), it can be clearly seen that the β phase becomes more homogeneous than that in the microstructure of as-rolled sheets (Fig. 1 (b)).

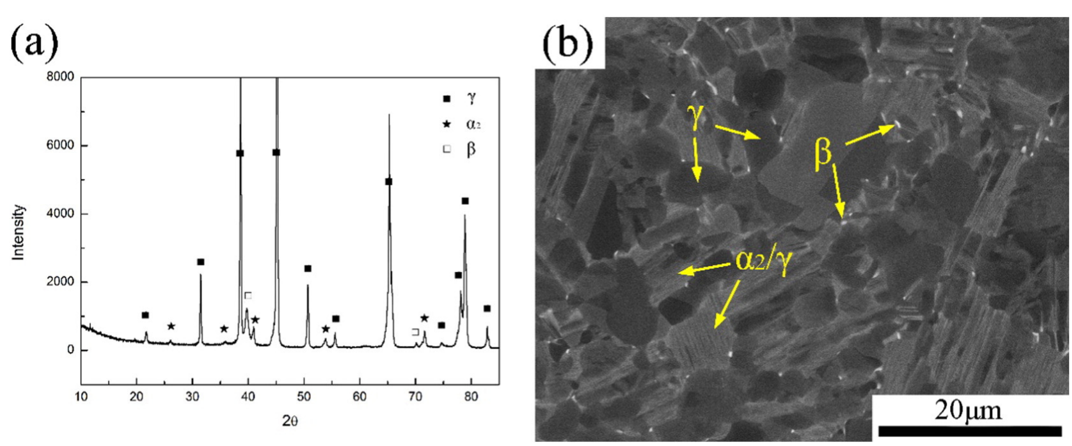

Fig. 1. XRD pattern (a) and SEM backscattered electron (BSE) image (b) of the as-rolled Ti-45Al-7Nb-0.3W (at.%) alloy sheets.