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In-situ SEM observations of fracture behavior of BT25y alloy during tensile process at different temperature

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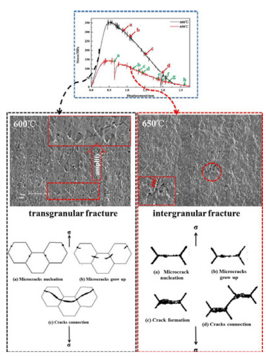
HIGHLIGHT

- High temperature tensile fracture behavior of BT25y alloy are observed by in-situ tensile observation.
- Fracture mechanism changes from transgranular at 600 °C to intergranular at 650 °C.
- Interface strength is lower than grain strength when the deformation temperature is over 650 °C.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to characterize the fracture behavior of BT25y alloy at different temperature, in-situ scanning electron microscopy of this alloy was performed during high temperature tensile deformation process. The results showed that microcracks mainly initiated at α/α and α/β interfaces during both 600 °C and 650 °C tensile process. However, the path of crack propagation varied at different temperature, it was related to the rapid decline in interface strength with deformation temperature increasing. When deformed at 600 °C, interface strength was higher than grain strength, cracks propagated into grain interior, the tensile specimen presented transgranular fracture characteristic. As the deformation temperature increasing to 650 °C, interface strength was lower than grain strength, cracks tended to propagate along interfaces, and the tensile specimen presented intergranular fracture characteristic. Mechanical performance was sensitive to deformation temperature, with the temperature increasing from 600 °C to 650 °C, the ultimate tensile strength fell by 200 MPa.

1. Introduction

(α + β) titanium alloys are attractive for aerospace and marine applications as structural materials due to their high specific strength, excellent thermal resistance, good room temperature plasticity, superior fatigue and creep strength [1–5]. Among the explored (α + β) titanium alloys, BT25y alloy (Ti-6.5Al-2Sn-4Zr-5Mo-1W-0.2Si, wt%) with outstanding high temperature properties, is designed for high temperature applications up to 600 °C as compressor disk and blade of advanced engines [6]. A great deal of researches have been carried out on element content, phase transformation, microstructural characteristics and their effects on the mechanical properties of this alloy in the past few years [7,8]. However, direct reports on observations of the microprocess

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of fracture are rarely reported. For structural application, such as engine, the deformation and fracture behaviors also need to be investigated in detail, since fracture failure seriously deteriorates the mechanical performances. In addition, deformation temperature affects the fracture behavior. At present, the highest service temperature of titanium alloy is 600 °C [9]. A sharp drop in high temperature strength will happen with the service temperature over 600 °C, due to the gliding of grain or phase boundaries participating in deformation process with temperature increasing [10]. Less works have been done to study the distinction of fracture behavior between 600 °C and over 600 °C. In the present investigation, 600 °C and 650 °C tensile deformation process and fracture behaviors of BT25y alloy were investigated by in-situ scanning electron microscopy (SEM). This research will help in understanding the relationship between temperature and fracture mechanism.

2. Experimental

BT25y alloy used in this study was melted by triple vacuum arc remelting processing. The ingot after homogenized at 1100 °C for 1 h was broken down and forged to billets. The billets were then hot rolled at 900 °C into round bars with 12 mm in diameter. The composition of the investigated alloy was 6.6% Al, 1.93% Sn, 3.89% Zr, 4.6% Mo, 0.96% W, 0.23% Si (wt), Ti balance. The β transus temperature (T_β) of the alloy was about 960 °C measured by metallographic techniques. In general, microstructure plays an important role in the mechanical properties of titanium alloys [11]. Bi-modal microstructure, with 20– 30% equiaxed primary α phase and lamellar transformed β structure, exhibits better room temperature ductility and high temperature strength [12]. In this research, the forged bar was homogenized at 940 °C for 2 h followed by air cooling to acquire bi-modal microstructure, in which the primary α phase showed an equiaxed shape and distributed homogeneously in lamellar transformed β structure, as shown in Fig. 1. The microstructures were observed by Axiovert 200 MAT type Zeiss metallographic microscope (OM) and JSM-7001F scanning electron microscope (SEM). The samples for OM and SEM observation were prepared according to conventional metallographic techniques and etched with Kroll's reagent (5 vol% HF + 15 vol% HNO_3 + 85 vol% H_2O) to reveal grain/phase boundaries [1].

In-situ tensile specimens were machined from the bar via electric discharge machining, dimension of the specimen was presented in Fig. 2a. The specimens were electro-polished in a solution of 6 vol% perchloric acid and 94 vol% acetic acid before testing. In-situ observations during tensile process were performed in CS-3400 type scanning electron microscopy. Tensile tests were performed using a loading stage (maximum load capacity: 1KN) placed inside the SEM chamber, as shown in Fig. 2b. The specimen was strained at a strain rate of 0.0005 mm/s. During tensile process, at certain load levels, as shown in Fig. 3, the tensile process was paused and the load was held, and then SEM images were taken. It should be pointed out that a slight stress relaxation occurred during the pauses. After imaging, the load or displacement rate was continued at the same level.

3. Result and discussion

3.1. In-situ tensile curves

Typical tensile stress-displacement curves at high temperature are shown in Fig. 3. Various stress levels at which the test is paused for SEM imaging are marked on these plots. The curves exhibit peak flow stress followed by continuous dynamic softening. Furthermore, flow stress decreases with increasing the tensile temperature, due to the motion of dislocation and interface become easier at higher temperature [13,14]. The ultimate tensile strength (UTS) of BT25y alloy at 600 °C is about 200 MPa higher than that at 650 °C.

3.2. Microcrack nucleation and propagation

In-situ SEM tensile deformation is adopted to study the fracture behavior of BT25y alloy at different temperature focusing on the microcrack nucleation and propagation process. Fig. 4 shows the in-situ SEM images of BT25y alloy taken at sequential load levels during 600 °C tensile process. Before the stress reaching UTS, there is no defect could be observed on the surface of the specimen. As the strain increases further, tensile stress decreases, microcracks nucleation along α/α and α/β interfaces are observed at stress about 300 MPa, as shown in Fig. 4a. The size of nucleated microcrack is about 20 nm, however, the maximum size of microcrack can be observed under the electron microscope is about 500 nm. Therefore, the nucleated microcrack has grown up when it begins to be found by SEM. The number of microcracks increases with the strain increasing, and the microcracks mainly distribute along α/α and α/β interfaces (Fig. 4c). Red rectangle field in Fig. 4 represents the same location, and this field is amplified as shown in the top right corner of Fig. 4b, d. From this enlarged view, it can be clearly observed that the crack propagates through the interior of α and β phase. It's indicated that transgranular fracture happens in BT25y alloy during 600 °C tensile process. Meanwhile, the width of crack increases with the strain increasing.

Fig. 5 shows the in-situ SEM images of BT25y alloy during 650 °C tensile process. This specimen exhibit the same phenomenon of microcracks nucleation, as for the specimen deformed at 600 °C. Microcracks nucleate along interfaces at stress about 135 MPa, as shown in Fig. 5a. With the strain increasing, the number of microcracks increases, and the microcracks also mainly distribute along α/α and α/β interfaces, as shown in Fig. 5c and d. As the strain increases further, the cracks propagate along interfaces. Unlike the 600 °C tensile process, only intergranular cracks distribute in the specimen surface could be observed in Fig. 5e. With the tensile process continues, the width of crack increases from tiny crack to cavity, as shown in the red circle field of Fig. 5h.

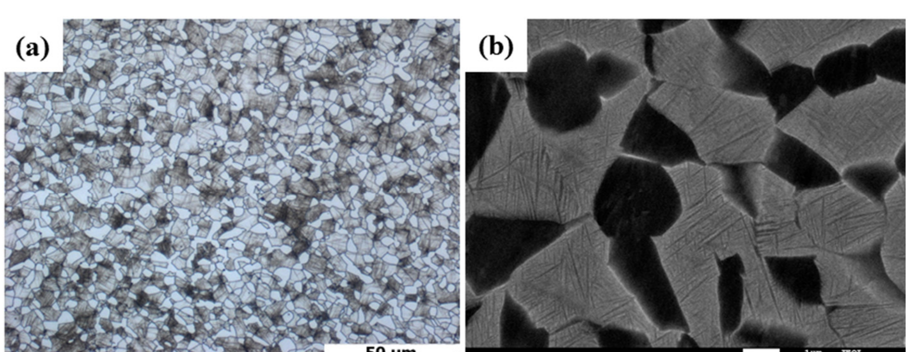

Fig. 1. Microstructure of BT25y alloy heat treated at 940 °C/2 h, AC: (a) OM and (b) SEM.