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The cavitation of high Nb-containing TiAl alloys during tensile tests around BDTT

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ABSTRACT

To understand the fracture behavior and cavity evolution of high Nb-containing TiAl alloys, tensile tests were conducted at low strain rates and various temperatures around brittle to ductile transition temperature (BDTT). Then, the fracture morphology and cavitation behavior were investigated. The results show that cavitation occurs above BDTT as the fracture mode changes from cleavage fracture to ductile fracture. And the cavitation of this alloy is dominated by diffusion-controlled cavity nucleation, which is promoted at higher temperature. The growth and coalescence of cavities are correlated with heterogeneous deformation and facilitated at higher strain rate. The cavity growth and coalescence are accelerated at boundaries between hard and soft orientated lamellar colonies due to the strain incompatibility. Additionally, β/B2 phase may facilitate the cavity nucleation due to its high diffusivity. These findings may provide important implications for optimizing the hot-working processing of high Nb-containing TiAl alloys.

1. Introduction

High Nb-containing TiAl alloys have attracted increasing attentions due to their excellent creep property and oxidation resistance [1,2]. The addition of Nb leads to large amounts of metastable β/B2 phase, which enormously improves the hot workability [3–5]. However, the cavities formed under tensile stresses during thermal-mechanical processing leads to defects and even catastrophic failure, which reduces the production efficiency and thus impedes the commercial-application advance of TiAl alloys.

The cavitation is generally divided into stages of nucleation, growth, and coalescence. It has been demonstrated that cavities nucleate preferentially at grain boundaries or second-phase particles due to the co-effect of stress concentration and vacancy accumulation [6,7]. Cavity growth normally occurs by diffusion related mechanisms, such as surface diffusion and grain boundary diffusion, or plastic deformation of the surrounding material [8,9]. The dominant mechanism of cavity growth varies with cavity size and deformation conditions. Cavity coalescence is the linkage of small cavities with the entire volume being conserved, which occurs in the end and results in final fracture [10].

The cavitation behavior of TiAl alloys has been observed in a considerable amount of researches about the creep and superplastic deformations. It is illustrated that the cavity nucleation and growth of lamellar TiAl alloys are related to colony boundary sliding [11,12]. And dynamic recrystallization suppresses the cavity growth due to the release of stress concentration [11,13]. The cavitation of both fine and relatively coarse-grained two-phase near-γ TiAl alloys is dominated by plasticity-controlled cavity growth [13,14]. And the cavity growth rate decreases with an increase in temperature and a decrease in the strain rate due to the increasing strain accommodation and dynamic recrystallization. However, only simplified phenomenology illustration are provided in most of these researches, and the systematical analyses of the cavitation mechanisms are insufficient. Besides, few attentions have been paid to multi-phase high Nb-containing TiAl alloys and the effect of β/B2 phase is not clear. Nieh et al. [15] suggested that β/B2 phase could reduce the cavity formation through accommodating the sliding stains, which was consistent with the investigations conducted by Wang et al. [16] and Zhang et al. [17]. Nevertheless, the research of Cheng et al. [18] claimed that the growth and coalescence of cavities are accelerated due to the specific deformation mechanism caused by the presence of β/B2 phase. And it was recently observed by Wang et al. [19] that the β segregation (i.e. blocky β/B2 + γ phases at colony boundary) promoted colony boundary sliding and the formation of voids.

To systematically investigate the fracture and cavitation behavior of high Nb-containing TiAl alloys, uniaxial tensile tests were conducted around BDTT. Morphology observation and quantitative analysis of cavities were performed to study the nucleation, growth and coalescence processes. The roles of heterogeneous deformation and phase

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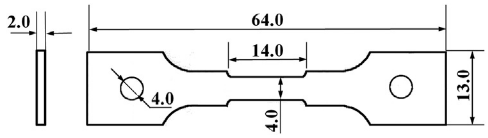

Fig. 1. Geometry of a tensile specimen used for elevated temperature tensile tests (dimensions in mm).

constituents, especially the β/B2 phase, in the cavitation of TiAl alloys are explored thoroughly.

2. Experimental description

The materials used in this study were sampled from an industrial plasma arc melted ingot with a nominal composition of Ti-45Al-8.5Nb-0.2W-0.2B-0.02Y (at%). The ingot was in as-cast condition without homogenization or stress-relief heat treatment. The flat tensile specimens (Fig. 1) were cut from the ingot using electrical discharge machining and mechanically ground to remove the cut surfaces. X-ray flaw detection and density measurement were performed after specimen preparation to exclude specimens with solidification defects. Tensile tests were performed on a DDL50 electronic universal testing machine in air at temperatures from 700 °C to 900 °C with different strain rates. An extensometer was attached to the gauge section of the specimen during tensile tests to obtain the strain data and ensure a constant strain rate. The furnace chamber was opened immediately after tensile tests to preserve the microstructure.

After tensile tests, a Tescan VEGA II LMH scanning electron microscopy (SEM) was used to observe the fracture morphology using the secondary electron (SE) mode. And half of each fractured specimens were sectioned longitudinally to establish cavitation behavior. Overall and detailed analyses of the cavitation behavior were separately performed on a Leica DM-4000M optical microscopy (OM) at 100 times magnification and on the SEM at 500 times magnification using the back scattered electron (BSE) mode. The specimens were sectioned along the mid-thickness plane and vibratory polished with colloidal silica to prevent alteration of the cavity morphology. Cavities of diameter less than 1 μm were ignored to avoid measurement error for both analyses. The analysis zones were generally in dimensions of 3 mm × 1 mm for SEM analysis. To investigate the correlation between cavitation behavior and heterogeneous plastic deformation, electron backscattered diffraction (EBSD) was conducted on a Tescan MIRA SEM. A step size of 1 μm was used in the EBSD analysis and the γ phase was indexed as generic face-centered cubic structure.

3. Results and discussion

3.1. Initial microstructure

The BSE image and the corresponding EBSD map of the high Nb-containing TiAl alloy are shown in Fig. 2. The raw material exhibits a lamellar $\alpha_2(Ti_3Al)$ + γ(TiAl) structure with γ grains (grey contrast) and residual β/B2 phase (bright contrast) presenting at colony boundaries and triple junctions, as shown in Fig. 2(a). The colony size of the material is about 50–100 μm. Yttrium oxides (white particles) and borides (grey particles and rods) distribute heterogeneously in this alloy, as indicated by white arrows. Fig. 2(b) shows the inverse pole figure (IPF) map of γ major phase at the same location. Due to the distortion arising from the 70° tilt during EBSD, the orientation map doesn't seem to coincide with the BSE image precisely in every detail. The β/B2 phase and the α_2 phase are indexed in green and yellow, respectively. Since a cubic symmetry was assumed for γ phase, the γ lamellae in one colony are indexed into two twin groups. The color bands in lamellar colonies normally cover tens of γ lamellae dominated by γ variants of one twin group, as indicated in our previous work [20]. The α_2 lamellae are hardly indexed because of their relatively low lamellar thickness. As shown in the EBSD map, most of the γ grains at colony boundaries possess the same crystal orientation as the γ lamellae in the adjacent lamellar colony. It reveals that the equiaxed γ grains observed in the BSE image are mostly resulted from discontinuous coarsening of γ lamellae rather than direct nucleation in the retained β/B2 phase [21].

3.2. Mechanical behavior

The mechanical behavior under tensile load of the high Nb-containing TiAl alloy is shown in Fig. 3. Fig. 3(a) shows the true stress vs. true strain curves at temperatures between 700 and 900 °C with strains rates of 3×10^{-5}/s and 3×10^{-4}/s. An elongation of 7.5% was used for defining the BDTT [22]. It shows that the BDTT of the as-cast TiAl alloy is between 700 and 850 °C at the strain rate of 3×10^{-5}/s, and increases to 850–900 °C at 3.8×10^{-4}/s. The specimens were hardly deformable and failed in a brittle fashion below BDTT, while significant increases in plasticity were obtained above BDTT. A plateau is expected at high strains in the tensile curves above BDTT. However, the tensile curves show a linear decrease of the stress with increasing strain after reaching a maximum value at a strain around 4%. The decrease of the stress is mainly attributed to the inevitable decrease of true strain rate due to the necking of the specimen, and the growing role of softening processes, such as dynamic recovery and recrystallization. Additionally, the formation of cavities also contributes to the softening of the TiAl alloys, which will be discussed in the following.

The strain rate vs. peak stress σ_p diagram is shown in Fig. 3(b). The stress exponent, n, can be defined as $[\partial \ln\dot{\varepsilon}/\partial \ln\sigma_p]_T$, where T denotes temperature. It is demonstrated that n varies from 13.5 to 5.6 as the test temperature changes from 850 °C to 900 °C. The variation of the stress

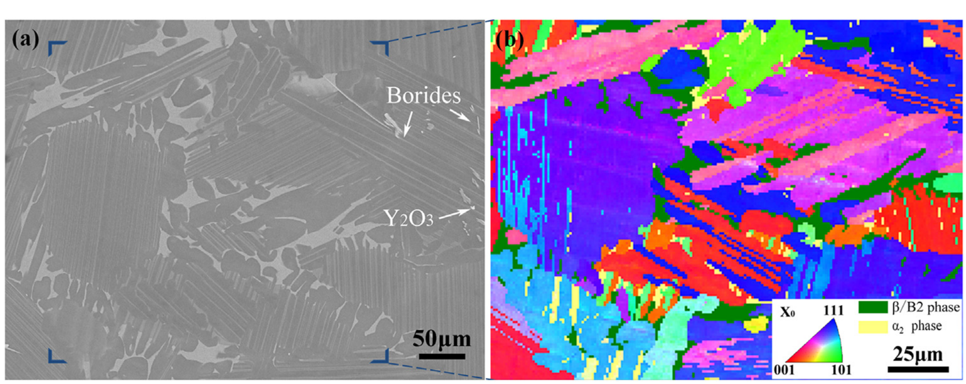

Fig. 2. (a) BSE image and (b) IPF map of γ major phase obtained from the raw material of the high Nb-containing TiAl alloy.