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Effects of loading rate on damage and fracture behavior of TiAl alloys

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Abstract

Based on the results of tensile tests and notch 3PB tests with various loading rates and the observation of fracture surfaces, the effects of loading mode and rate on damage and fracture mechanisms of fully lamellar (FL) and duplex phase (DP) TiAl alloys are indicated:

(1) For the FL specimen fractured in tensile test, a number of interlamellar cracks occur before final fracture, which is produced by the cracking of the area remained between the existing cracks on a most weakened cross-section. However the DP specimen in tensile test is fractured by the propagation of a crack with a critical length acting as a Griffiths crack in brittle materials. In the 3PB tests of notched specimens the fracture mechanism is different with that in the tensile tests. Crack initiates at the notch root and propagates along a strip around the center line where the normal stress is highest. For FL specimen a more tortured path through low-resistance-interlamellar cracks can be taken at a low loading rate. Because of the low resistance and the rate-dependence of the interlamellar cracking, the loading rate affects significantly the fracture mode.
(2) Based on the variation of the fracture mechanisms, the reason why the FL alloy shows inferior tensile properties but matching even superior fracture toughness to the DP alloy is explained further incorporating the effects of loading rate.
(3) The tensile strength and fracture toughness show a decreasing trend with lowering loading rate and it is associated with rate-dependent interlamellar cracks involving in the fracture process.

Keywords: TiAl alloys; Fracture mechanisms; Fracture toughness; Loading rate; Damage

1. Introduction

The fracture behavior of TiAl alloy has been investigated thoroughly. Kim and Dimiduk described that the room temperature (RT) fracture in duplex phase (DP) TiAl alloy is dominantly transgranular cleavage-like failure, often exhibiting river patterns. Fully lamellar (FL) specimens exhibit three characteristic fracture features at RT: translamellar fracture, interlamellar fracture and a mixture depending on the lamellar orientation with respect to the crack path or stress axis [1]. Chan et al. revealed an initiation toughness as low as 1.17 MPa m$^{1/2}$ exhibited in a binary TiAl alloys and attributed it to the interlamellar fracture by interface debonding [2].

Inui et al. [3] investigated the tensile deformation of polysynthetically twinned (PST) crystals of TiAl and found that the tensile elongation to fracture, as well as the yield strength, strongly depended on the angle between the lamellar interfaces and tensile axis. A largest tensile elongation of 20% and the lowest yield strength around 100 MPa (lowest yield shear stress around 50 MPa) were obtained for specimens with an angle of 31°. Akiyama et al. [4] studied directionally solidified ingots composed of columnar grains with lamellar aligned with various angles to the crack propagation direction. In their work, the fracture toughness of specimens with lamellae perpendicular to the precrack was much higher than that of specimens with lamellae parallel to the precrack. The present authors [5] indicated that in thin specimens, cracks preferred to initiate and propagate at the interfaces between lamellae before plastic deformation. The driving force for fracture development was the tensile stress, the interlamellar cracks could be produced at a normal stress as low as around 50 MPa, which was lower than the yield stress in

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the soft orientation [3,6]. The interlamellar crack bypassed the grain with unfavorable orientation along the grain boundary or stretched through it by translamellar crack.

The inverse relationship between tensile ductility and fracture toughness of coarse grain fully lamellar (FL) TiAl alloy was revealed by Chan and Kim [7]. The difference between the greater amount of general yielding strain of DP structure in tensile and the near crack tip effective strains of the lamellar structure was used to explain the inverse relationship between ductility and fracture toughness.

The present authors [8] suggested a mechanism that the inverse relationship between tensile strength (ductility) and notch toughness of coarser near fully lamella microstructures was caused by the difference of the propagation paths (fracture mechanisms) taken by the crack in the tensile specimen and in the notch bending specimen.

Zheng et al. [9] investigated the effects of microcracks on the plastic deformation of a fully lamellar (FL) γ-TiAl alloy. In the research several results related to this paper were obtained.

While the FL TiAl alloys deformed at relative low strain-controlling rates ($1 \times 10^{-5}\,s^{-1}$), a large number of microcracks nucleated within the grains that led to the following conclusions:

(1) Fracture load decreased with increasing microcrack density. The larger the grain size, the higher the microcrack density, thus, the higher the apparent plasticity and the lower the fracture stress.
(2) The apparent plastic elongation incorporates both plastic strain and the elongation which was caused by microcracks.

In Ref. [10] Bartels et al. investigated the strain rate dependence of the deformation mechanisms in a FL γ-TiAl alloy and concluded. The cracking behavior depends on the strain rate, at a strain rate of $5 \times 10^{-3}\,s^{-1}$(quasi-static conditions) the FL samples show large cracks in the direction of the compression cone, whereas dynamically compressed specimens ($(2–4) \times 10^{3}\,s^{-1}$) exhibit a high number of interlamellar microcracks. Obviously, the high strain rate diminishes the crack initiation rate and crack propagation.

In Ref [11] Zhou et al. indicated that the tensile strength and the strain to fracture increased with increasing strain rate.

Table 1
Compositions of TiAl alloy (at%)

Ti	Balance
Al	47.5
V	2.5
Cr	1.0

In authors' previous papers [12], the following effects of microcrack-damage on fracture behavior of TiAl alloy were proposed: (a) microcracks that developed on the weakest cross-section determined the fracture load (referred to as the facial effects). (b) Microcracks produced through the entire specimen volume decreased the apparent elastic modulus and resulted in a descendant sector in the load–displacement curve just before final fracture (referred to as the volumetric effects). (c) The large lamellar cracks showed a rate-dependent character.

From these results, it was inferred that the higher the loading rate, the lower the density of microcracks, and the higher the fracture stress. In this paper this inference is examined and observations focus on the different fracture mechanisms as shown in tensile tests and three point bending (3PB) tests of notched specimens. The inverse relationship of coarse FL TiAl alloy showing inferior tensile properties but superior fracture toughness is analyzed and discussed on the base of the difference of fracture mechanism.

2. Experimental procedure

2.1. Materials and specimens

A TiAl alloy with compositions shown in Table 1 was used. All samples were taken from a forged pancake that had been deformed at 1100 °C to achieve a 70% height reduction. The samples were first treated by hot isostatic pressing in 950 °C, at 120 MPa in argon for 3 h, then wrapped in quartz tubes and put into a furnace at pre-determined temperatures. Duplex (DP) microstructure samples were obtained by annealing at 1260 °C for 12 h, cooled in the furnace, and fully lamellar (FL) microstructure samples were obtained by annealing at 1370 °C for 3 h, cooled in the furnace. The two types of microstructures (DP with grain sizes of around 50 μm, and FL with grain size of around 1000 μm) are shown in Fig. 1.

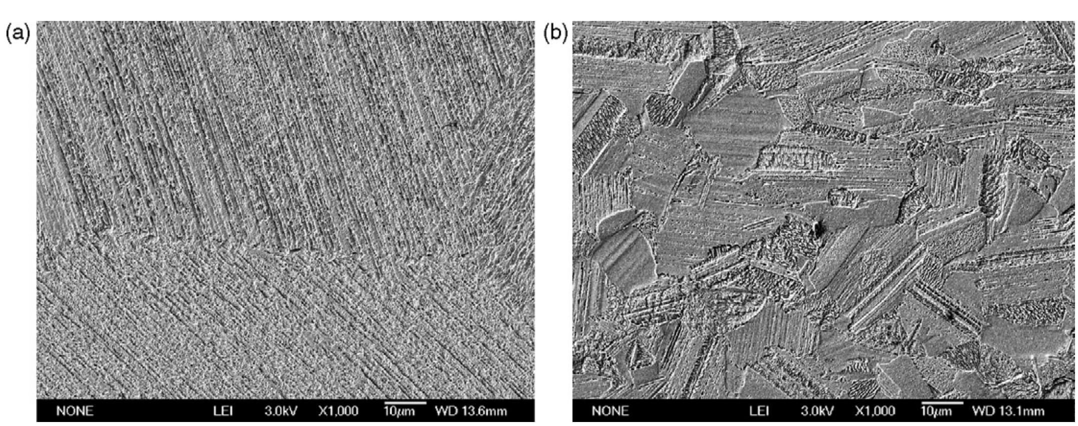

Fig. 1. Microstructures of (a) fully lamellar and (b) duplex TiAl-based alloy.