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Study on compression deformation, damage and fracture behavior of TiAl alloys: Part I. Deformation and damage behavior

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ABSTRACT

The compression deformation, damage and fracture behaviors of TiAl alloys in the fully lamellar and duplex microstructures were systematically studied. The fracture behaviors in compression tests of TiAl specimens are detailed in Part II of this work. In this paper a series of compression preloading–unloading–reloading tests were carried out. Results indicated that the compression engineering stress–strain curves were unchanged and were not affected by the numbers of multiple preloading–unloading processes until the preloading stresses reached the ultimate compression stress. However the tensile strength was significantly reduced by the multiple compression preloading–unloading–reloading processes. At the microscopic scale, the development of the microcracks on the specimen surfaces increases up to ~1000 cracks/mm^2 with the compression up to the ultimate fracture stress of ~2200 MPa. The linking of microcracks to form macrocrack damage in the bulk is examined. A preloading–unloading–reloading process with step-by-step observation of the initiation, extension and formation of microcracks on the specimen surface with increasing compression load is described in detail. From these observations, mechanisms of crack linking and propagation are identified in duplex and fully lamellar microstructures.

1. Introduction

In the past two decades, γ-TiAl-based alloys have received tremendous attention for high-temperature and high-performance structural applications, primarily due to their low density, high strength to weight ratio as well as their good creep and oxidation resistance [1,2]. However, some of the properties of intermetallic materials such as toughness and formability at room temperature are poorer than those of conventional metallic structural materials. Therefore their application is limited. Since the 1980s, a great number of studies for fracture mechanism of TiAl alloys in tensile have been done and a series of systematic results have been achieved [3–5]. In authors' previous papers [6,7], the following effects of microcrack damage on tensile fracture behavior of TiAl alloy were proposed: (a) microcracks that developed on the weakest cross-section decreased the fracture strength (referred as the facial effects), (b) microcracks produced through the entire specimen volume decreased the apparent elastic modulus and resulted in a descending section in the load–displacement curve just before final fracture (referred as the volumetric effects), (c) the large inter-lamellar cracks (100–300 μm) showed a rate-dependent character

However, the reports on compression deformation and fracture behavior are relatively rare. A large difference of deformability between tensile and compression tests was caused by the difference of stress and strain conditions. Ref. [8] showed that the yield strength was a function of the test temperature measured by compression tests at various test temperatures.

Ref. [9] shows that there are three modes of crack initiation and propagation in the compression loading tests as shown in Fig. 1, the compression axis is horizontal in all figures: cracks initiate and propagate along grain boundaries or inside the grains and the crack orientation is parallel to the compression axis (a). In Fig. 1(b) three cracks initiate and propagate at the intersection of three grain boundaries, yielding two mode II and one mode I cracks. In Fig. 1(c) two cracks propagate along the compression axis which initiate at either end of an inclined mode II precrack, which is produced at an inclined grain boundary. In compression stress regions, micro-

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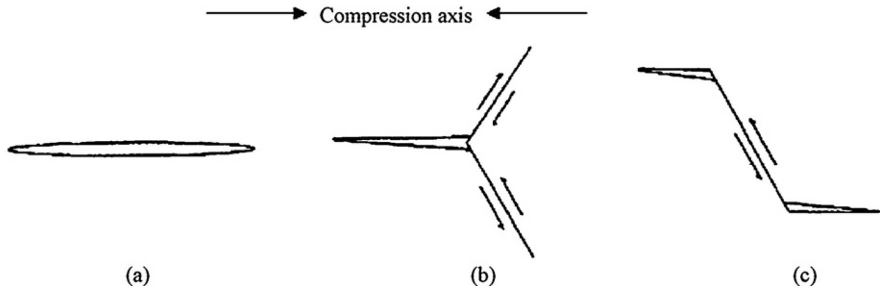

Fig. 1. Three types of crack initiation and propagation in the compression loading mode [9].

Table 1
Compositions of TiAl alloy (at%).

Ti	Al	V	Cr
Balance	47.5	2.5	1.0

cracks nucleate at the precrack tips, cavities, inclusions and other defects. With increasing applied load, some cracks can propagate and connect with each other to form a macroscopic crack and finally induce the specimen fracture.

In engineering applications, compression effects appear on the blades of the combustion gas turbine by continuous start–shut down of the compressible gas. Specially, in the case of the connection made by inserting the shaft of the TiAl wheel into a K418 alloy sleeve with the interference fit, the extra high compression stress maybe causes the cracking within the TiAl shaft. Therefore the compression deformation, damage and fracture behaviors of TiAl alloys deserve to be studied to identify the correct design criteria to produce optimal performance for many engineering components.

2. Experimental

2.1. Material and specimens

A TiAl alloy with the elemental compositions shown in Table 1 was used. All samples were taken from a forged pancake that was deformed at 1100 °C to a 70% height reduction. Two types of microstructures, duplex (DP) and near fully lamellar (FL) as shown in Fig. 2 were obtained with the following heat treatments. The samples were first put in a quartz tube, treated by hot iso-static pressing at 950 °C and 120 MPa in argon for 3 h and then put into the furnace at pre-determined temperatures. DP microstructure samples were obtained by annealing at 1250 °C for 18 h, and FL microstructure samples by annealing at 1370 °C for 1 h.

The average colony (grain) size and the average lath width of FL microstructure (Fig. 2(a)) were measured as 200–300 μm and 2–3 μm, respectively. The average grain size of the DP microstructure (Fig. 2(b)) was 20–30 μm.

Rectangular specimens (12 mm × 5 mm × 5 mm) were used for all compression tests. The specimens were unloaded after single or multiple preloading–unloading (PU) processes at various levels of preloading stresses. One group of specimens were used for observing microcracks and measuring their densities on the surfaces of specimens unloaded at each level of PU process. The second groups of specimens were used to obtain the effects of PU processes on the consequent compression reloading behavior. The prior two groups of specimens were never dismounted with the PUR process. The third group of specimen (special specimen FL-C-08) was used for characterizing the initiation and extension of the main crack. This specimen was unloaded at some unloading stress, and then the specimen was dismounted to observe microcracks of specimen's surface. Finally, the specimen was reloaded to other applied stress. The process of loading–unloading–dismounting–observation–reloading was repeated until specimen's fracture.

The fourth group of specimens (a special type of specimens) was made for observing the effects of multiple compression preloading–unloading–reloading (PUR) processes on the strength of consequent tensile tests. The dimensions of these special rectangular compression specimens were 60 mm × 25 mm × 25 mm. After multiple PUR, three tensile specimens were cut from each compression specimen, the orientations of the tensile specimens are parallel with the compression axis of the special compression specimens. The dimensions of tensile specimens are shown in Fig. 3(a). The thickness was varied to keep the larger cracks within a given specimen as shown in Fig. 3(b).

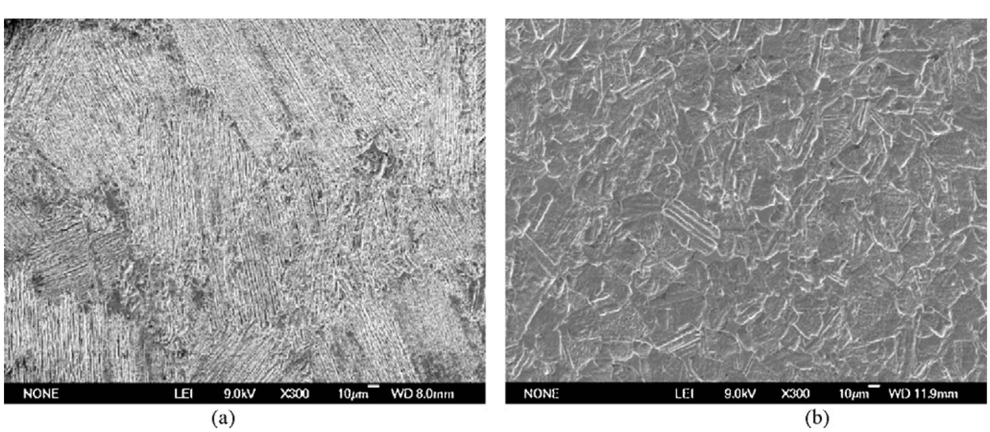

Fig. 2. Microstructures of (a) fully lamellar and (b) duplex TiAl-based alloy.