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On the role of thermal exposure on the stress controlled fatigue behaviour of a high strength titanium–aluminum alloy

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ABSTRACT

Fatigue specimens with four types of surface were assessed under three exposure conditions (no exposure, block exposure, individual exposure–oxidation at 700 °C for 10,000 h) to quantify the effects of surface roughness, stress concentration, oxidation and inner microstructural embrittlement on fatigue strength of a near lamellar γ-TiAl alloy Ti–44Al–4Nb–4Zr–0.2Si–1B. With the yield strength of $\sigma_{0.1}=621$ MPa, *S–N* fatigue is found to be always conducted under a loading condition of $\sigma_{max}<\sigma_{0.1}$. Local plastic deformation is difficult to occur on the maximum-stressed surface. The surface quality with or without defects and residual stresses therefore becomes critical for fatigue performance. Introducing compressive-stressed layer by shot peening and removing tensile-stressed layer and defects by grinding-electropolishing can improve the fatigue strength significantly, and the latter is more capable than the former for the high strength alloy. It is found that the fatigue performances of all types of surface are deteriorated to some degree when subjected to block exposure, owing to exposure-induced embrittlement. On the other hand, exposure-induced fatigue strengthening occurs after individual exposure–oxidation. The relaxation of residual tensile stress and dissipation of bulk stress in warm-air environment are found to outweigh the negative effects of oxidation layer at surface and exposure-induced embrittlement inside specimen.

1. Introduction

γ-TiAl based intermetallic alloys exhibit much steeper fatigue crack growth resistance curves and lower fracture toughness than conventional Ti-based and Ni-based alloys. Such characteristic features give rise to a relatively narrow interval between the threshold stress intensity factor range ΔK_{th} and the maximum stress intensity factor K_{max} at final failure [1–5]. The fraction of total fatigue life resulting from crack propagation is therefore significantly small, and the total life is likely to be dominated by the number of cycles to crack initiation. Based on this behaviour, one approach to a reliable prediction of fatigue life for γ-TiAl alloys is to use conventional *S–N* fatigue curves. Fatigue strength, as a representative of fatigue crack initiation resistance, is considered to be one of the primary design drivers for TiAl alloys [6–8].

In view of the importance of endurance limit based on *S–N* performance, there is a need to develop a clear understanding of how surface defects and other stress concentrators, caused by component design, manufacturing and machining, impact of foreign object and surface oxidation, affect the total life of γ-TiAl alloys under cyclic loading. The degree and extent to which fatigue strength is reduced by surface defects and stress concentrators should be assessed quantitatively. This becomes particularly important since γ-TiAl alloys often exhibit a relatively flat fatigue *S–N* curves [9–11]. Any stress raisers in components, even on a small scale, could cause over-stressing and thus unexpected early failure. Considerable amounts of research have been carried out to qualify the effects of surface quality [12–15], notch [16,17], foreign object damage [18,19] and oxidation layers [20,21] on fatigue life of TiAl alloys. However, no much effort in this area has been made for γ-TiAl alloys which are subjected to a long-term thermal exposure. A γ-TiAl based alloy component in service is in fact exposed to elevated temperatures (say 700 °C) in air environment for long time (say 10,000 h). Three major types of microstructural/micromechanical changes are expected to occur: (a) internal microstructural changes due to constituent dissolution, decomposition and phase transformation, (b) surface layer oxidation and (c) changes in suface and bulk stress concentration since long-term exposure in a thermal enviroment. Therefore, it is necessary to assess all the surface defects and stress concentrations on total life under the condition of long-term thermal exposure in air.

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The present study concentrates on all these effects on the total life of a high-strength, fine-grained γ-TiAl alloy. The alloy is to be studied under three thermal exposure schemes: (a) no exposure, (b) block exposure with internal changes but no surface oxidation, (c) thermal exposure with both internal changes and surface oxidation. The main objective of the study is to reveal how and to what extent the varied surface and bulk material under the three thermal exposure schemes affect the fatigue crack initiation resistence of the high strength TiAl alloy. This work concerning damage tolerance capability in real service is expected to provide a reference guide for safe applications of TiAl alloys at elevated temperatures.

2. Experimental

The γ-TiAl based alloy in this study is a grain refined, high strength ($\sigma_{0.1}=621$ MPa) near lamellar alloy Ti–44Al–4Nb–4Zr–0.2Si–1B (alloy 4Nb–4Zr). The alloy ingot was produced using a double-melted PACH (Plasma Arc Cold Hearth) process. The ingot received was approximately 100 mm in diameter, and was hot isostatically pressed (HIPped) at 1260 °C under a pressure of 150 MPa for 4 h. The alloy composition was determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) for the main elements, and is Ti–43.73Al–4.14Nb–4.12Zr–0.24Si–1.01B (at%).

Three groups of specimens with different thermal exposure history were prepared for *S–N* fatigue testing: Group A, no exposure; Group B, exposure in ingot block without oxidation; Group C, individual specimen exposure with surface oxidation. Fatigue specimens of dimensions $10\times10\times70$ mm^3 were machined from as-HIPped ingot. Four surface conditions were prepared for each group: plane-sided EDM wire, V-notch, shot-peened and electropolished. The details of the preparation procedures were listed in Table 1. A 60° V-shaped notch (V-notch) with a root radius of 0.20 mm and overall notch depth of 1.75 mm ($K_t=3$, where K_t is the theoretical elastic stress concentration factor) was introduced. Notch was machined using one pass EDM wire, same as plane-sided EDM specimens. Shot peening was carried out by means of an injector type system using ϕ 0.4–0.5 mm sized zirconia-based ceramic spheres at an air-jet pressure of 5×10^5 Pa. The peening was done to achieve a full coverage of the maximum-stressed surface area. Electropolishing was carried out on mechanically ground and polished samples and performed at 20 V in an electrolytic solution of 6% perchloric acid, 35% butanol and 59% methanol at −25 °C.

Surface roughness was measured using an Ambios XP-2 profilometer over a distance of 5 mm and represented in a standard Ra value. The Ra value listed in Table 2 is an average of 5 measurements for each surface condition, with an error range assessed by standard deviation. The surface roughness was measured before individual exposure–oxidation for Group C, which was measured in the same batch with non-exposed Group A. Therefore, samples in Group C and A display the same surface roughness. However, due to 10,000-h exposure before shape machining and surface preparation, the surface roughness of Group B specimens shows values slightly different from those in Group A and C.

Microhardness profiles were measured to characterise the compressively strained surface after shot peening. The measurements were conducted on a HXD-1000TM Vickers microhardness tester with a load of 100 g.

After surface preparation, specimens in Group A were fatigue tested directly (named “no exposure”), while those in Group C were exposed individually in an air-circulated furnace at 700 °C for 10,000 h (named “individual exposure–oxidation”), and then tested after exposure. In contrast to Group C, Group B was exposed as a 100 mm diameter ingot block (named “block exposure”) in the same furnace at 700 °C for 10,000 h, and then machined to shape and prepared for the same four surface conditions, followed by fatigue testing. It appears that all specimens in Group B experience interior microstructural changes but no oxidation at the surface.

S–N fatigue tests were carried out at room temperature in ambient air. Four point bending samples were tested on a PLG-100 electromagnetic resonance testing machine at a frequency of 100–120 Hz under a stress ratio R of 0.1 (where $R=\sigma_{min}/\sigma_{max}$, and σ_{min} and σ_{max} are the minimum and maximum stresses applied over the fatigue cycle respectively). Testpiece run-out was defined for specimens not failing after 10^7 cycles. The fatigue limit σ_{FL} is typically defined by the value of σ_{max} at run-out ($\geq10^7$ cycles).

The prepared surfaces and microstructures before and after thermal exposure were examined by scanning electron microscopy (SEM) utilising either secondary electron (SE) or backscattered electron (BSE) mode. The average colony/grain size, obtained from more than 1000 colonies/grains, was determined using linear interception method. The volume fraction of α_2 and γ phases was measured using Image J software on several BSE images. Detailed microstructure before and after thermal exposure were also studied by transmission electron microscopy (TEM) using a JEOL 2010 FX microscope operating at 200 kV. Thin foils were prepared by twin-jet polishing with an electrolyte of 5 vol% perchloric acid, 30 vol% butan-1-ol and 65 vol% methanol, operating at 30 V and at a temperature of −30 °C. For all image analyses, mean values were determined with a standard deviation to represent the uncertainty of the measurements.

3. Results

3.1. The microstructure before exposure

The microstructure of the alloy 4Nb–4Zr before exposure is shown in Fig. 1a. The alloy after HIPping essentially shows a near-

Table 1
The preparation procedure of the maximum stressed surface for fatigue tests.

Surface	Preparation procedure
EDM wire	One pass EDM wire to shape
V notch ($K_t=3$)	One pass EDM wire to shape
Shot peening	One pass EDM to shape, grinding, shot peening
Electropolishing	One pass EDM to shape, grinding and polishing, electropolishing

Table 2
Surface roughness Ra (μm) with error range for each surface condition.

Specimen (Group)	EDM (A, C)	Shot peening (A, C)	Electropolishing (A, C)	EDM (B)	Shot peening (B)	Electropolishing (B)
Surface roughness Ra (μm)	4.60 ± 0.13	1.51 ± 0.20	0.31 ± 0.03	5.22 ± 0.10	1.55 ± 0.11	0.32 ± 0.04