Intermetallics 85 (2017) 1–14

Contents lists available at ScienceDirect

Intermetallics

journal homepage: www.elsevier.com/locate/intermet

Fatigue response of a grain refined TiAl alloy Ti-44Al-5Nb-1W-1B with varied surface quality and thermal exposure history

Z.W. Huang [a, b, *], J.P. Lin [c], Z.X. Zhao [a], H.L. Sun [a]

[a] School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, Sichuan, 610031, China
[b] School of Metallurgy and Materials, The University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
[c] State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing, 100083, China

ARTICLE INFO

Article history:
Received 26 August 2016
Accepted 23 January 2017

Keywords:
Titanium aluminides
Electron microscopy
Fatigue behaviour
Oxidation
Phase transformation
Thermal stability

ABSTRACT

Fatigue specimens with four types of designed surface (EDM plane-sited, EDM notched, shot peened, electropolished) were assessed under three exposure conditions (no exposure, block exposure, individual exposure-oxidation at 700 °C for 10000 h) to quantify the effects of surface roughness, stress concentration, oxidation and inner microstructural embrittlement on fatigue behaviour of a grain refined TiAl alloy Ti-44Al-5Nb-1W-1B. With the yield strength of 568 MPa, fatigue is found to occur under a loading condition of $\sigma_{max}<\sigma_{0.1}$. Local plastic deformation is difficult to occur. The alloy becomes sensitive to surface damages but not to V-notch because the small surface area sampling the highest stress significantly reduces the EDM impact. Electropolishing rather than shot peening is found to be more effective in improving fatigue strength for the high strength alloy. When subjected to block exposure, both annealing effect (beneficial) and microstructural embrittlement (detrimental) occurred on all the surfaces, and the latter was dominant in governing fatigue behaviour except for EDM surfaces. After individual exposure-oxidation, fatigue performance deteriorated significantly for the shot peened and moderately for the electropolished but not for EDM surfaces. The mechanism for specific fatigue behaviour is discussed individually based upon whether or not the beneficial effects outweigh the detrimental effects.

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 result in 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 the 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 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, much less 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 (e.g. 700 °C) in air environment for long time (e.g. 10000 h). Three major types of microstructural and micromechanical changes are expected to occur: a) internal microstructural changes due to constituent

* Corresponding author. School of Metallurgy and Materials, The University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK.
E-mail address: z.w.huang@bham.ac.uk (Z.W. Huang).

http://dx.doi.org/10.1016/j.intermet.2017.01.010
0966-9795/

dissolution, decomposition and phase transformation, b) surface layer oxidation and c) changes in surface and bulk stress concentration. It is necessary to assess the influence of all these changes on total life under the condition of long-term thermal exposure in air.

The present study concentrates on all the three types of 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 designed surfaces and bulk material under the three exposure schemes affect the fatigue performance of the high strength TiAl alloy.

2. Experimental

A grain refined, high strength ($\sigma_{0.1}$ = 568 MPa) near lamellar alloy Ti-44Al-5Nb-1W-1B (alloy 5Nb-1W-1B) is used in this study. The alloy ingot was produced using a double-melt 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, followed by a stabilisation heat treatment at 900 °C for 24 h. The composition was analysed using inductively coupled plasma atomic emission spectroscopy (ICP-AES)). The alloy was determined to be Ti–44.3Al–5.05Nb–0.85W–0.83B (all in at. %).

Three groups of specimens with different thermal exposure history were prepared for S-N (Stress-Number of cycles to failure) fatigue testing: Group A, no exposure; Group B, exposure of ingot block without surface oxidation; Group C, individual specimen exposure with surface oxidation. Fatigue specimens of dimensions 10 × 10 × 70 mm^3 were machined from the ingot. Four types of surface were prepared for each group: a) plane-sided EDM (electrodischarge machining), b) V-notch by EDM, c) shot-peened and d) electropolished. The details of the preparation procedures were listed in Table 1. After surface preparation, specimens in Group A were fatigue tested directly (named “no exposure”), while specimens in Group C were exposed individually in an air-circulated furnace at 700 °C for 10000 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 10000 h, and then machined to shape and prepared for the same four surfaces, followed by fatigue testing. All specimens in Group B experience interior microstructural changes but no oxidation on the surface.

A 60° V notch with a root radius of 0.20 mm and overall notch depth of 1.75 mm was introduced (Kt = 3, Kt is the theoretical elastic stress concentration factor). Notch was machined using one pass EDM wire, same as for plane-sided EDM specimens. It should be noted that the notch was introduced after block exposure for Group B but before individual exposure-oxidation for Group C. For Group A, it was introduced and tested directly. For shot peening samples, a 150–200 μm thick layer introduced by EDM was removed by mechanical grinding before peening. 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 conducted on mechanically ground and polished surface 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 4 measurements for each surface, with an error range assessed by standard deviation. The surface roughness of Group A and B under the same surface condition is very similar, although all the surfaces in Group B were prepared after 10000-h block exposure. The surface roughness values are therefore listed together for the two groups. On the other hand, the surface roughness of Group C specimens was measured after exposure-oxidation. As seen in Table 2, long-term oxidation caused a noticeable increase in Ra for each surface.

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 300 g. The distance of the indentation marks was greater than five indentations apart. The results presented are the average of the three-five measurements per position. The average standard deviation of the hardness values was 24 HV0.3 in Group A and B and 18 HV0.3 in Group C.

S-N fatigue tests were performed at room temperature in ambient air. Four point bend samples (70 × 10 × 10 mm^3) were loaded with a maximum stressed span of 20 mm and a distance of 20 mm between the inner and outer rollers. Testing was conducted on a PLG-100 electromagnetic resonance machine 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) at a frequency of ~100 Hz. 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 ($\geq 10^7$ cycles). For multiple run-outs, a lower value was used for defining the fatigue limit.

The prepared surfaces and microstructures before and after thermal exposure were examined by scanning electron microscopy (SEM) under either secondary electron (SE) or backscattered electron (BSE) mode. Energy-dispersive X-ray spectroscopy (EDS) analysis was conducted on oxidised surface. The volume fraction of lamellar colony, and β and γ grains was measured using Image J software on BSE images. The colony/grain size, obtained from more than 1000 colonies in SEM BSE images, was determined using a mean linear-interception method. 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 % butane-1-ol and 65 vol% methanol, operating at 30 V and at a temperature of −30 °C. Centered dark field technique was used to image the phases concerned. The α_2 lamellae thickness and volume fraction were measured by tilting the foils such that the lamellar interfaces were edge-on (i.e. orientated along $<1\bar{1}0>_\gamma // <11\bar{2}0>_{\alpha 2}$ directions). A linear-intercept method using AxioVision software was used for quantifying such parameters. For all image analyses, mean values

Table 1
Preparation procedures for the maximum stressed surfaces.

Surface	Preparation procedure
EDM wire	One pass EDM wire to shape
V notch (Kt = 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