High Cycle Fatigue Properties of Ti-834 Following Prolonged Thermal Exposure in air

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The effect of surface finish has been studied on the high cycle fatigue endurance limit of a near-alpha titanium alloy IMI 834. Following exposure in air at 650℃ for durations up to 1500 hrs, both shot peened and machined specimens were tested using a staircase loading method at R=0.1 to measure the 10^7 plain fatigue endurance limit. The fatigue limits for both the shot peened and machined conditions were similar for unexposed specimens. Thermal exposure at 650℃ in air however, led to an increase in the fatigue limit for machined specimens, and a lowering of the fatigue limit in the case of shot peened specimens. Surface microcracks within the specimen gauge were observed to form more readily in the shot peened material. The increased propensity for surface crack initiation in peened specimens following thermal exposure in air is ascribed to the accelerated diffusion of interstitial oxygen within the cold-worked surface region.

Keywords: *Shot peening, alpha-case, thermal exposure, silicides, Ti-834, high cycle fatigue testing*

1. Introduction

The creep resistant near-alpha titanium alloy Ti-834 is an advanced aero-structural material employed in the intermediate and high pressure compressor stages of gas turbine aero-engines. Due to its use in the "hot end" of aero gas turbine engines for the manufacture of compressor discs, rings and blades; Ti-834 posses a good combination of creep and fatigue properties (in addition to oxidation resistance) up to its service temperature of 600℃[1]. Regions of the compressor assembly, such as the loading slot/blade root, are often shot peened prior to assembly in order to improve service fatigue performance and handling properties during assembly. The cold work introduced along a components surface during shot peening leads to the formation of an in-plane compressive residual stress below the treated surface, which retards the propagation of surface nucleated cracks[2]. Further to this, the increase in dislocation density and commensurate work hardening of the surface layer may also impede fatigue crack initiation. Whilst the general beneficial effects of peening on the plain and fretting fatigue properties of titanium alloys are well documented[3,4], literature pertaining to the effect of shot peening on the high cycle fatigue properties of titanium alloys following prolonged thermal exposure is more limited.

In addition to studies investigating the stability of shot peened induced residual stresses during elevated temperature exposure[5], recent research has shown that peening accelerates surface oxygen uptake in Ti-834 during long-term thermal exposure in air[6]. An increase in the measured subsurface oxygen levels is accompanied by the precipitation of $(Ti,Zr)_xSi_y$ silicides along mechanical twin boundaries and within regions of high dislocation density. It can be anticipated that the increased levels of subsurface oxygen content associated with shot peened material will to some degree influence the fatigue properties of the alloy due to the embrittling effects of interstitial oxygen in alpha-titanium[7,8]. Although it is well documented that the beneficial effects of shot peening on fatigue performance are negated during elevated temperature exposure due to relaxation of the compressive residual stresses, it is plausible that microstructural changes and increased surface oxygen levels induced by shot peening are deleterious to the integrity of a component.

To compliment the microstructural analysis that has been performed on shot peened Ti-834[6], this research aims to identify whether the high-cycle fatigue properties following high temperature exposure are adversely affected by the peening process. Furthermore, the fatigue testing programme is intended to provide the design engineer with preliminary data to construct Haigh diagrams and mapping the acceptable unacceptable fatigue loading conditions for machined and shot peened material. In order to benchmark results against the traditional "worse case" scenario for surface condition, shot peened material is compared with specimens tested in the as-machined condition. The fatigue testing programme is also supplemented by preliminary fractography and microstructural to examine the mechanisms that control high cycle fatigue life in machined and shot peened surface conditions.

2. Experimental Methods

Forged Ti-834 billet was supplied by TIMET UK and the chemical composition of the material is given in Table 1. The billet was slowly cooled following hot working low in the $(\alpha+\beta)$ phase and was not subject to any further processing or heat treatment for the purpose of this study. The microstructure of the supplied forging is shown in Figure 1 and is comprised of a large volume fraction of primary alpha in a matrix of coarse transformed beta lamellae. This microstructural condition differs from the conventional *bi-modal* type, which is typically observed in solution heat treated and aged material.

Table 1. Chemical composition (wt. %) of the Ti-834 billet supplied by TIMET UK. Analysis was performed at INCO Test, UK.

Al	Sn	Zr	Nb	Mo	Si	C	Ti
5.5	4	3.5	0.8	0.5	0.3	<0.1	Bal.

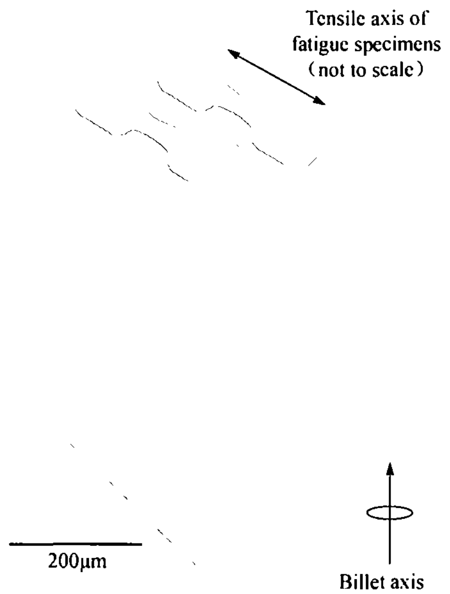

Figure 1. Starting microstructure of the Ti-834 billet, schematically showing the orientation of the fatigue specimens with respect to the billet axis

Fatigue testing was performed using Amsler M8 specimens. The test specimen configuration results in a gauge diameter and a 25 mm gauge length. An advantage of employing this type of test specimen design is that the surface to volume ratio is maximised, thus the surface effects to fatigue life are more pronounced. A disadvantage however, is that the small cross-sectional area of the test specimen lends itself to interference from the large regions of microtexture (termed *macrozones*), which exist in this alloy and have been thoroughly characterised by electron backscatter diffraction[9].

Amsler M8 fatigue specimens were machined from the received billet of Ti-834 such that the stress axis was perpendicular to the billet axis as shown schematically in Figure 1. Tensile testing of the supplied billet was performed under quasi-static loading conditions with the specimens machined such that the tensile loading axis with respect to the billet coordinates was identical to that used in the fatigue testing programme.

A number of fatigue specimens were shot peened to 200% coverage at 9A Almen intensity using R32 steel shot at Metal Improvement Company, Derby, UK. The specimen thread was protected during the shot peening process and only the gauge length was treated. Specimens were tested in the as-machined and shot peened conditions both prior to, and following thermal exposure at 650℃ in laboratory air. Due to the limited number of available fatigue specimens and the large number of experimental variables, a staircase loading method[10] was chosen to assess the high cycle fatigue limit of the shot peened and machined specimens. The fatigue tests were performed at a frequency of 66 Hz in laboratory air and at a stress ratio of 0.1. A mean positive tensile stress for the fatigue testing was employed to preserve the fracture surfaces following failure for examination. The constant life fatigue endurance limit ($\Delta\sigma_{ES}$) was then calculated using the following equation[10]:

$$\Delta\sigma_{ES} = \Delta\sigma_{PS} + (\Delta\sigma_F - \Delta\sigma_{PS}) * (N_f/N_{RO}) \quad (1)$$

Where $\Delta\sigma_{PS}$ is the stress range of the penultimate loading step, $\Delta\sigma_F$ the stress range of the loading step required for failure, N_F the number of cycles to failure in the final loading step and N_{RO} the number of cycle considered a run out, which was 10^7 cycles in this study.

Analysis of the fracture surfaces was performed on the failed specimens using an FEI Sirion field emission gun scanning electron microscope. A selected number of fractured fatigue specimens were sectioned parallel to the tensile loading axis and prepared for metallography. Initial grinding was performed using water lubricated silicon carbide grinding papers to achieve a planar finish. Preliminary polishing was performed using 9 μm diamond suspension and final polishing with a 0.06 μm colloidal silica suspension.

3. Results and Discussions

The room temperature tensile properties of the supplied Ti-834 forging are presented in Figure 2. The

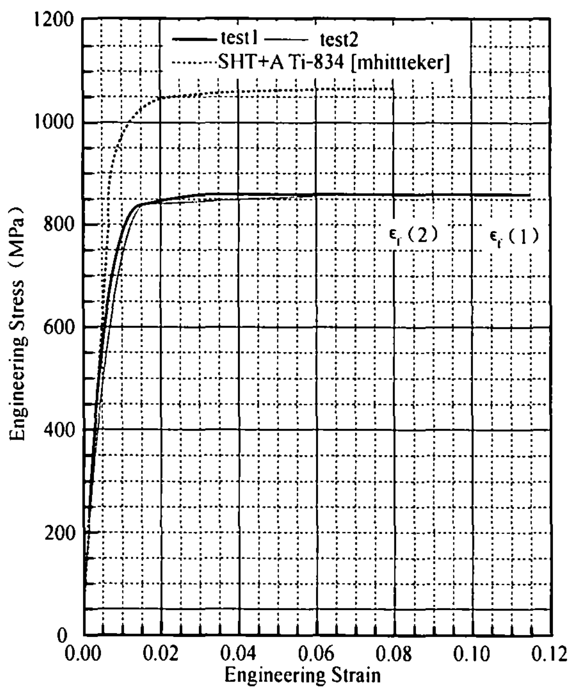

Figure 2. Tensile properties of the received Ti-834. The tensile behaviour of solution heat treated and aged Ti-834 from Whittaker[11] is shown for comparison

0. 2% offset yield strength calculated from both tensile tests was 790 MPa, with the two specimens failing at strains of 0. 07 and 0. 1. Tensile properties of Ti-834 in the solution heat treated and aged condition from Whittaker[11] are shown as comparison.

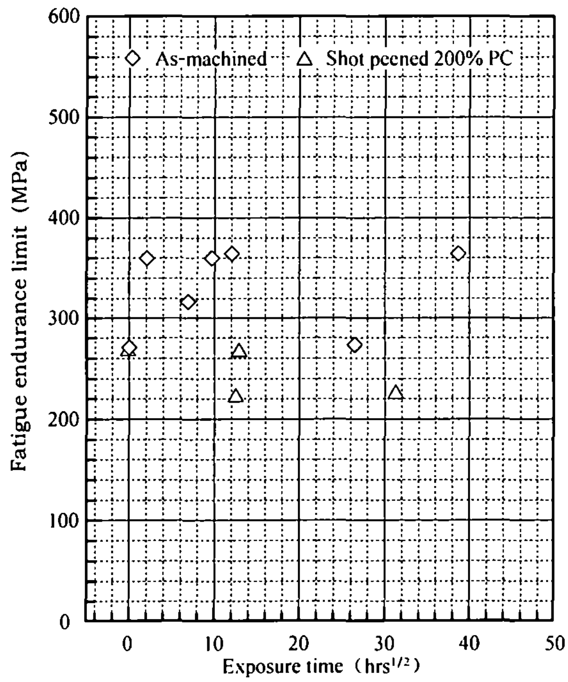

Figure 3. High cycle fatigue endurance limits for shot peened and machined Ti-834 specimens following thermal exposure in air at 650℃. The constant life endurance limit ($\Delta\sigma_{ES}$) was calculated from equation (1)

Figure 2 shows the constant life endurance limits for machined and shot peened Ti-834 following thermal exposure in air at 650℃. Data for the fatigue endurance limits were collected using the staircase loading method and calculated using equation (1). For specimens tested in the as-machined and shot peened conditions, there is negligible difference in the constant life fatigue endurance limit, with the calculated endurance stress range being in the region of 270 MPa for the two surface conditions. Both the room temperature tensile yield strength and the high cycle fatigue endurance limit of Ti-834 as measured in this study are lower than those reported by other researchers and the manufacturer's datasheet. This is likely to result from the lack of strengthening modes which occur during the 700℃ ageing step in fully heat treated materials, such as α_2 and silicide precipitation. In the case of the machined specimens, short thermal exposure durations lead to an initial increase in the fatigue endurance limit. This trend is not anticipated based on the assertion that surface oxygen contamination is deleterious to the fatigue properties of titanium alloys[8]. It would be expected that even short exposure times to air would lower the fatigue limit of the alloy. This discrepancy may firstly be due to the relaxation of the deleterious residual stresses introduced during the machining operation. Secondly, it is plausible that for short exposure times the limited diffusion of oxygen into the specimen surface leads to a local strengthening effect without a significant loss in ductility, therefore suppressing fatigue crack initiation at the surface. With increasing surface oxygen levels however, reduced defect sensitivity will lead to a lowering of fatigue initiation lives.

Fractography of the fatigue specimen tested following thermal exposure for 1500 hrs (Figure 4) shows circumferential faceting to a depth of approximately 50 μm below the surface (Region A in Figure 4). Whilst no definitive crack initiation site can be identified, evidence of crack penetration into the substrate in the form of closely aligned facets can be seen in regions B and B'. Evidence of extensive fluting within the ductile overload region can be seen in region C, suggesting that slip has become more planar in nature within the specimen bulk. This is likely to be a resultant effect of short range ordering of aluminium to form α_2 precipitates during thermal exposure.

Surface microcracks can be observed close to the fracture surface in the cross-sectional light micrograph shown in Figure 5a). Surface microcracking within the specimen gauge was not observed in the machined fatigue specimens thermally exposed to air for shorter durations. It is therefore apparent that a threshold alternating or mean stress to initiate surface microcracks within the oxygen enriched zone exists, and that this stress decreases with increasing thermal exposure time in air.

Shot peening results in a lowering of the fatigue endurance limit following comparatively short thermal exposure times as is shown in Figure 2(b). Figure 5(b) is a cross-section light micrograph through the gauge length of the shot peened fatigue specimen following thermal exposure for 160 hrs at 650℃. Small microcracks can be observed within the surface region and penetrate to a depth of approximately 50 μm. The distribution of the surface microcracks is fairly uniform, with an average crack spacing of 50 μm. This result demonstrates that surface microcracks are able to form more readily in shot peened material during fatigue loading following thermal exposure in air. Whether a relationship exists between the relative ease in which surface microcracks form during fatigue loading and the final failure mode are directly linked requires further investigation. The stress ratio of $R=0.1$ employed in the course of this testing programme would encourage subsurface/microstructural mechanisms to control fatigue failure, whilst fully reversed loading ($R=-1$) would generally favour surface crack initiation[12]. Nevertheless, the experimental evidence suggests that peening promotes surface crack initiation in thermally exposed Ti-834 and it is therefore important to consider the effects of surface treatment on the fatigue properties of such high temperature titanium alloys.

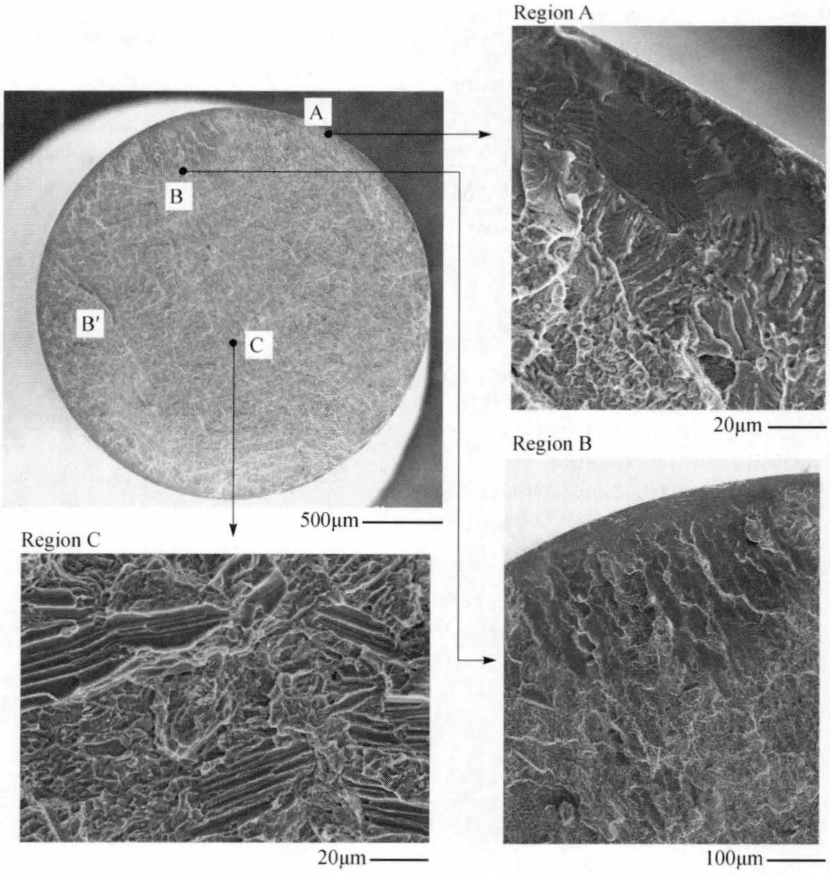

Figure 4. Secondary electron SEM micrographs showing the fracture surface of a machined Ti-834 fatigue specimen tested following exposure to laboratory air for 1500 hrs at 650℃. Higher Circumferential faceting around the fracture surface can be observed and higher magnification SEM micrographs of the regions labelled A, B and C are also shown

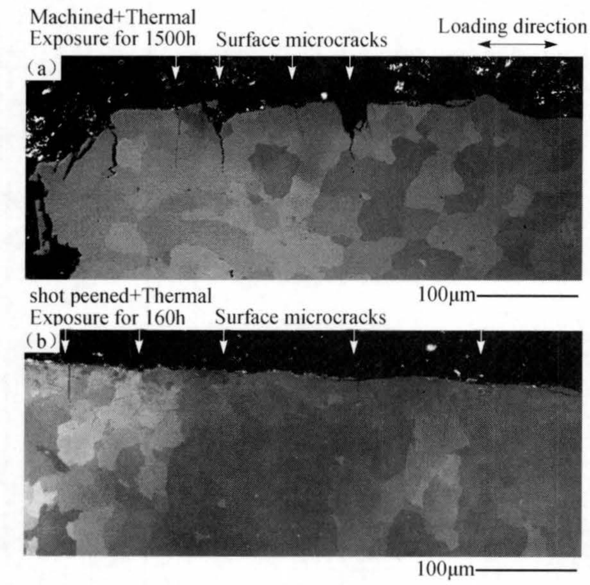

Figure 5. Cross-section polarised light micrographs of (a) machined and (b) shot peened fatigue specimens tested following thermal exposure at 650℃ for 1500 h and 160 h respectively

4. Summary and Conclusions

The effect of shot peening on the high cycle fatigue endurance limit of the near-alpha alloy Ti-834 has been assessed following long-term high temperature exposure in air. Fatigue testing was performed at a constant stress ratio of R=0.1 using a staircase loading method and the results are compared against machined (not shot peened) specimens.

The difference in fatigue properties between shot peened and as-machined conditions prior to thermal exposure is negligible. Following thermal exposure at 650℃ however, the fatigue limit of machined Ti-834 increases whilst that of shot peened material decreases.

Surface microcracking is observed in machined specimens following thermal exposure in air for durations in excess of 1000 hrs and subsequent fatigue testing. In shot peened material, surface microcracks are observed after much shorter thermal exposure durations (circa 160 hrs).

Previous research has shown increased levels of surface oxygen content in shot peened Ti-834 when compared with a non-peened surface finish, and the increased propensity for surface microcracking in shot peened material is consistent with this result. The current mechanism proposed which.

The preliminary high-cycle fatigue data collected during this testing programme has indicated that shot peening may be deleterious to the mechanical integrity of Ti-834 following high-temperature thermal exposure in air. The fatigue data set is at present limited however, and a continued programme of research is required to fully quantify the effects of peening on the high cycle fatigue behaviour of the alloy following thermal exposure.

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