Engineering Failure Analysis 61 (2016) 2–20

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

Understanding the “blue spot” Sodium chloride hot salt stress-corrosion cracking in titanium-6246 during fatigue testing at low pressure

E.A. Saunders [a,*], T.P. Chapman [b], A.R.M. Walker [c], T.C. Lindley [b], R.J. Chater [b], V.A. Vorontsov [b], D. Rugg [c], D. Dye [b]

[a] Rolls-Royce plc., Materials — Failure Investigation, Bristol BS34 7QE, UK
[b] Department of Materials, Royal School of Mines, Imperial College London, Prince Consort Road, London SW7 2BP, UK
[c] Rolls-Royce plc., Materials, Elton Road, Derby DE24 8BJ, UK

ARTICLE INFO

Article history:
Received 22 April 2015
Accepted 16 June 2015
Available online 23 June 2015

Keywords:
Hot salt stress-corrosion cracking
Titanium-6246
Fractography
Pressure implication
Novel technology application in failure analysis

ABSTRACT

During hot component fatigue tests there have been two cases of low life crack initiation of gas turbine rotating parts manufactured from the Titanium alloy Ti-6246. Both exhibited a small (~0.1 mm) elliptical ‘blue spot’ at the origin. Through validated striation count work and fracture mechanics it was established that fatigue had propagated with a near-nil initiation life. Early investigation suggested that the ‘blue spot’ was possibly a region of stage 1 fatigue growth, and was therefore a material behaviour concern with potential implications for service. During an investigation of a later cracking incident in this alloy, subsequently shown to have resulted from stress-corrosion cracking (SCC), near-identical fractographic characteristics to that seen in the “blue spot” were found that subtly differentiated it from stage 1 fatigue. Also, similar ‘blue spots’ have since been identified on Ti6246 Laboratory hot LCF test specimens and found to have been due to contamination by NaCl, through the application of focussed long-term EDX examination and other novel chemical analyses techniques. By the application of those techniques, fractography, and comparison against these specimens, Rolls-Royce and Imperial College London have collaborated to show that the original two component ‘blue spots’ were subtle examples of NaCl-related Hot Salt Stress-Corrosion Cracking (HSSCC). Such cracking has not been found to occur in service components, due to air pressure within the engine, and the effect is therefore confined to Laboratory and component tests at near-atmospheric pressure or below.

1. Introduction

Titanium and its alloys spontaneously form stable and continuous surface TiO_2 oxide films on exposure to oxygen – the “passive layer” – the reason for very good protection against corrosive attack [1–3]. Even when the passive layer is broken it instantaneously heals, so long as oxygen is not prevented from reaching it [2].

In addition to this corrosion resistance, high fatigue strength to density ratios [1,3,4] have ensured that titanium alloys have broad applications in aero-gas turbine engines [5,6].

In the gas turbine, due to these properties, there is a desire to use titanium as far back in the engine and at as high a temperature as possible [5], promoting increased strength, higher temperature-resistant alloy development [5,7]. One such is the lamellar-microstructure beta (β)-forged and alpha (α)-β solution heat treated α/β titanium alloy Ti–6Al–2Sn–4Zr–6Mo (Ti-6246) [3,5,8,9], which is found in many components such as compressor discs.

* Corresponding author.

http://dx.doi.org/10.1016/j.engfailanal.2015.06.008

Spin testing of such rotating parts is a fundamental requirement as part of the demonstration of component fatigue life [10].

Two such hot (350, 400 °C) cyclic fatigue spin tests were carried out on Ti-6246 components, and found cracked in low cycle fatigue (LCF) at unexpectedly short lives. For this article only, the two tests have been labelled as ST1 and ST2.

Initial macroscopic fractographic examination at Rolls-Royce revealed tiny optically blue-coloured elliptical features of ~0.1 mm dimension present at the origin of both component crack systems. These have come to be known as the "blue spot" (sometimes "blue/grey") [11]; Fig. 1.

The "blue spots" were bounded by an abrupt colour change that is unconventional compared to normal 'growth-out' temper-colouration on hot cyclic fatigue fracture surfaces [12,13].

Quantitative fractography and fracture mechanics had together indicated that propagation from the "blue spot" periphery had occurred with near-nil initiation life, whilst the initial flaw size calculated via fracture mechanics [14] approximated to the "blue spot" dimension. Thus, it was considered that there was a Ti-6246 material behaviour concern with potential implications for service.

Initial investigation deemed that fractographic characteristics within the blue spot resembled microstructure ("structure-sensitive"; Fig. 2) [15,16]. A stress-corrosion mechanism was considered, but at the time no corrosive species were identified using the available techniques on either ST1 or ST2. It was generally commented that the crack was due to low cycle fatigue (LCF) development, but, although describing the fractographic characteristics within the "blue spot", no conclusion could be given as to its nature or cause at that time.

A collaborative PhD project was set-up between Rolls-Royce plc (Materials) and Imperial College London, which partly aimed to further understand the 'blue spot' crack initiation mechanism [11]. A number of the concepts presented herein have formerly been aired in [11], whilst this article explores other specimen and spinning rig results and related issues — as presented orally in the Sixth International Conference on Engineering Failure Analysis on 9th July 2014 (Lisbon, Portugal).

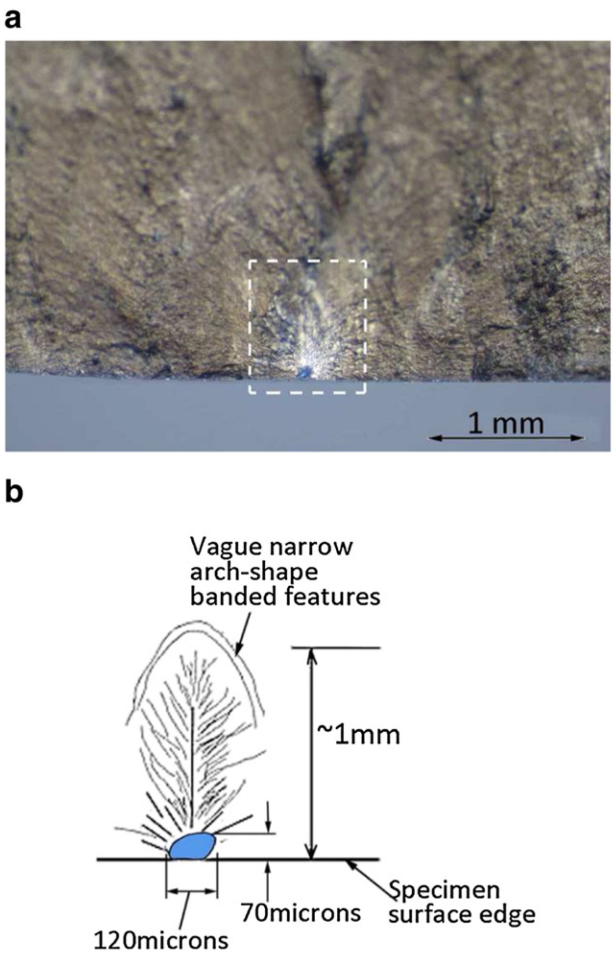

Fig. 1. (a) A 'blue spot' may be seen in this optical image of the ST1 crack origin on the fracture surface, located where an aligned alpha lath colony met the surface shown by the fern-shaped region of growth. Such microstructural features are not uncommon in this material (others may be seen in the image, without 'blue spots'). (b) Schematic of the area highlighted in (a). "Blue spots" in other specimens (including ST2) were not located at aligned alpha lath colonies or other particular microstructural feature.