Fatigue crack growth of a gamma titanium aluminide alloy

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ABSTRACT. Gamma titanium aluminide based alloys have emerged as important candidates for high temperature structural applications in the aircraft industry to replace current nickel-based superalloys as the material of choice for low-pressure turbine blades. This is primarily due to their low density, high specific stiffness, elevated-temperature strength retention, and relatively good environmental resistance. Although such materials appear very promising for the turbine engine industry, optimize the performances requires more advanced approaches to accurately predict fatigue life. Therefore, there is a need to understand and address the specific crack growth properties of these materials to assure adequate reliability of these alloys in structural applications. The long crack growth rate properties of a Ti-48Al-2Cr-2Nb alloy obtained by electron beam melting (EBM) with a patented process has been examined carrying out CPCA (Compression Pre-cracking Constant Amplitude) tests performed at different loading ratios and in-service temperatures.

KEYWORDS. Pultruded materials; Fatigue; Damage; Acoustic emission.

INTRODUCTION

Gamma titanium aluminide based alloys (γ-TiAl) have become an important contender for high temperature structural applications in the aircraft industry to replace current nickel-based superalloys as the material of choice for low-pressure turbine blades [1-2]. The advantages achieved by using of γ-TiAl intermetallics are mainly their low density (3.9-4.2 g/cm^3, depending on their composition), high yield strength, high stiffness, substantial resistance to oxidation and good creep properties up to high temperatures. In particular, the lower density contributes to significant engine weight reduction and reduced stresses on rotating components such as low-pressure turbine blades [3]. Although such materials appears very promising for the turbine engine industry, optimizing the performance improvements requires more advanced approaches to accurately predict fatigue life. Therefore, there is a need to understand and address the specific fatigue properties of these materials to assure adequate reliability of these alloys in structural applications [4]. Moreover, it is difficult to obtain a component produced with γ-TiAl intermetallics with exactly the composition and microstructure desired. A further difficulty is that in the typical aeroengines applications must have an extremely low oxygen content, preferably much lower than 1500 ppm.
Electron beam melting (EBM) is a type of additive manufacturing for metal parts. It is often classified as a rapid manufacturing method. The technology manufactures parts by melting metal powder layer per layer with an electron beam in a high vacuum. Using EBM technology, the process of material production operates under high vacuum conditions, thus reducing the risk of oxidation in the material of the final components. EBM technology for "layer by layer" productions offers several advantages with respect to other competing technologies and it is possible to operate at temperatures closer to the melting points of the intermetallic alloys [5]. In the EBM process, components are produced without vaporization of the powders of the initial material and the powders are made of an intermetallic alloy based on

titanium and aluminium with the same chemical composition as the final intermetallic with which the components are produced.
In the present work 6 Fatigue Crack Growth (FCG) tests have been conducted by means of CPCA test methodology in order to characterize the fatigue crack behaviour for the material under investigation.

MATERIAL AND SPECIMENS GEOMETRY

The gamma titanium aluminide (γ-TiAl) Ti-48Al-2Cr-2Nb alloy under investigation has been produced according to a patented process [6] with EBM A2 machine manufactured and distributed by ARCAM AB (Sweden), which allows focused electron beam melting to be performed in high vacuum conditions.
Material has been produced in the form of near net shape specimens and final notches were realized by wire EDM with selected cutting parameters, in order to avoid local modifications of the material microstructure. A set of 6 specimens suitable for crack propagation testing at room temperature have been produced with the geometry shown in Fig. 1.

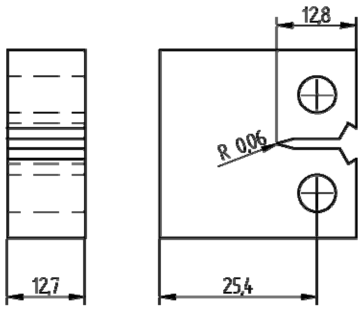


Figure 1: Shape and dimension of a fatigue crack propagation specimen.

Prior to RT (room temperature) fatigue testing, the surface of the specimens has been pre-oxidized, by furnace treatment in air for 20 hr at a temperature of 650°C [7].

TEST METHOD

Fatigue crack growth tests have been carried out in a servo-hydraulic MTS 810 testing machine and the crack length has been monitored by COD gage. The standard fracture mechanics specimens have been pre-cracked under cyclic compression. Compression pre-cracking has been applied to specimen by a home-made gripping system at the Mechanical Department of Politecnico di Milano, Fig. 2.

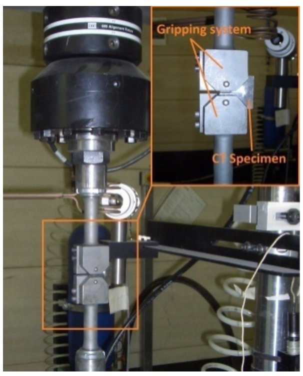
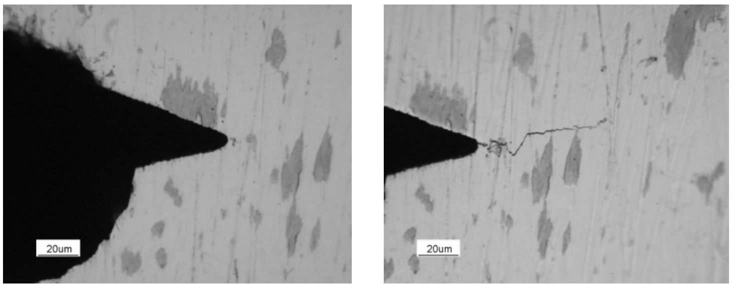


Figure 2: Gripping system for the application of a compression force at the specimen.

The crack closure effect at the beginning of the real crack growth test is avoided by pre-cracking specimens in cyclic compression. The starter notch was sharpened by a razor blade polishing technique [8] for starting a crack in cyclic compression by small load amplitudes.

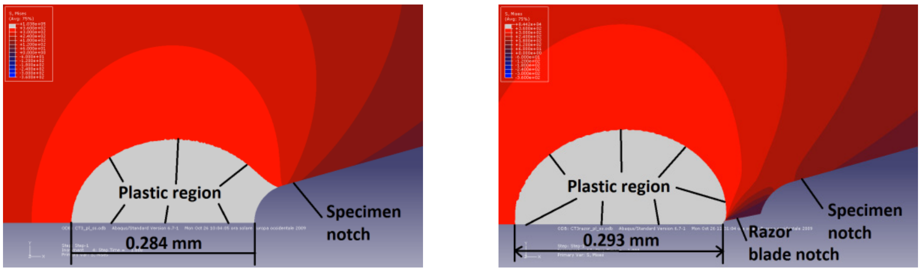
The effect of this technique and the initial crack, obtained by the compression pre-cracking procedure, is shown in Fig. 3a and 3b.



(a) (b)

Figure 3: Notch of the specimen: a) after razor blade polishing technique, b) pre-crack obtained after compression pre-cracking procedure.

Two finite element analyses (FEA) have been carried out in order to verify the effect of a sharpened notch on the length of the plastic region ahead the crack tip. It has been demonstrated that the pre-crack driving force is related to the magnitude of the residual stress field established during the first compressive cycle. The definition of the initial plastic extension is strictly related to the initial pre-crack. The analyses has been carried out by means of ABAQUS v. 6.9-1 [10]. Fig. 4a and 4b show the solutions in terms of von Mises stress distribution at the maximum compressive loads for the original notched specimen region (Fig. 4a) and for the razor blade notched specimen (Fig. 4b).



(a) (b)

Figure 4: FE results in terms of Von Mises stresses at the specimen notch: a) original; b) after razor blade polishing technique.

In order to determine the ΔK_{th} and the long crack propagation behaviour, FCG tests have been carried out at constant $R=K_{min}/K_{max}$ (R=0.05 and R=0.6) by increasing the load amplitude in steps until the threshold value for a long crack has been reached.

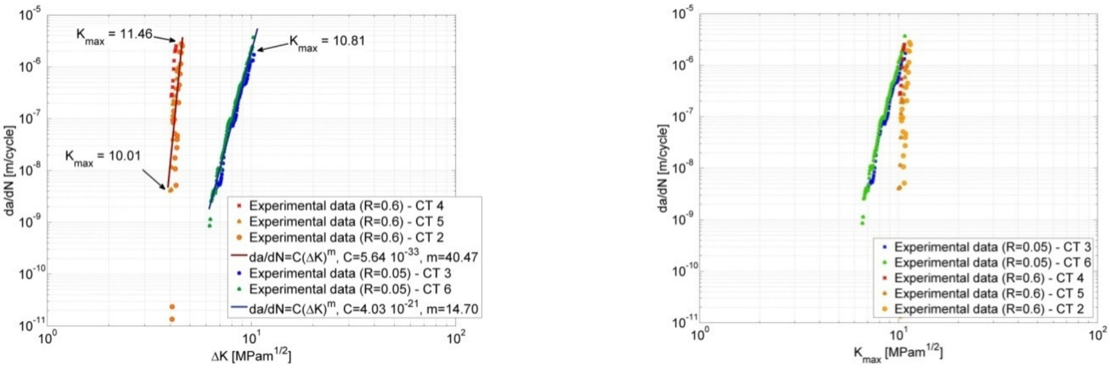
Experimental results

In the FCG tests conducted at R=0.05 no crack growth was observed for ΔK below 6 MPa√m, whereas for the tests at R=0.6, ΔK_{th} is about 3 MPa√m. The critical K_{max} value, corresponding to specimen failure, is in the range 10.5-11.5 MPa√m, independently of the applied $R=K_{min}/K_{max}$ ratio. The FCG rate curves are shown in Fig. 5. The threshold values determined here are in accordance with those reported in literature for the lamellar microstructure of γ-TiAl alloys [9].

It can be observed that the available ΔK range for crack growth is rather limited, due to the relatively limited difference between ΔK_{th} and K_{max}, resulting in high value of the slope.

Concluding remarks

A potential disadvantage for cast and PM γ-TiAl alloys, in terms of component design, is their limited fatigue crack growth resistance compared to nickel-based superalloys. In general, there is a small difference between the fatigue threshold stress-intensity-range of long cracks and the apparent fracture toughness, leading to shortened lifetimes for small changes in applied stress, should the fatigue threshold be exceeded. On the other hand, in the case of the Ti-48Al-2Cr-2Nb alloy examined in this work, the advantage of the γ-TiAl produced by the EBM process is that typical defects of cast or PM materials can be avoided resulting in higher fatigue threshold and fatigue strength respect to competing technologies.



(a) (b)

Figure 5: FCG rate curves in terms of: a) ΔK; b) K_{max}

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