Failure Analysis of a Fractured Control Pressure Tube from an Aircraft Engine

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***Abstract*—**This paper studies a failure case of a fuel pressure supply tube from an aircraft engine. Multiple fracture cases of the fuel pressure control tube from aircraft engines have been reported. The studied set was composed by the mentioned tube, a welded connecting pipe, where the fracture has been produced, and a union nut. The fracture has been produced in one of the most critical zones of the tube, in a region next to the supporting body of the union nut to the connector. The tube material was X6CrNiTi18-10, an austenitic stainless steel. Chemical composition was determined using an X-Ray fluorescence spectrometer (XRF) and combustion equipment. Furthermore, the material was characterized mechanically, by a hardness test, and microstructurally using a stereo microscope and an optical microscope. The results confirmed that the material was within specifications. To determine the macrofractographic features, a visual examination and an observation using a stereo microscope of the tube fracture surface were carried out. The results revealed a tube plastic macrodeformation, surface damaged and signs of a possible corrosion process. Fracture surface was also inspected by scanning electron microscopy (FE-SEM), equipped with an energy-dispersive X-ray microanalysis system (EDX), to determine the microfractographic features in order to find out the failure mechanism involved in the fracture. Fatigue striations, which are typical from a progressive fracture by a fatigue mechanism, were observed. The origin of the fracture was placed in defects located on the outer wall of the tube, leading to a final overload fracture.

***Keywords*—**Aircraft Engine, microstructure, fatigue, FE-SEM, fractography, fracture, fuel tube, stainless steel.

I. INTRODUCTION

THE fracture of fuel control pressure tubes can occur for many reasons, and when it takes place in a pipe carrying fuel, the situation can be potentially dangerous and can lead to a catastrophic failure [1], [2]. Numerous cases were cited in the literature whose main causes of failure have been the mechanisms of fatigue, corrosion, wear, creep and overload. But the most common failure cause in engine parts is the fatigue induced by a cyclic thermomechanical load, which can be accelerated by a corrosive atmosphere. Fatigue failure may also be caused by an incorrect manufacture, design or assembly of the tubes. Similar failures of afterburner fuel lines were presented various papers [3], [4], even causing fire in the jet engine [5]. Kral et al. [6] concluded in their study of an aircraft fuel line fractured, which caused an in-flight fire, that the fracture mechanism was likely to be fatigue due to vibrations.

Other authors [7], who studied the fractured rigid fuel injector line from a piston engine, determined that the fracture was caused by high-cycle fatigue and was initiated in one of the corrosion pits on the external surface of the line.

The Spanish Air Force has experienced several critical failures in the engine fuel lines of the MFCU (Main Control Fuel Unit) aircraft. This paper describes the investigation of a failure detected at the entry of the aircraft on the take-off runway, so there was no irreparable damage. After returning to the parking lot, several inspections were performed and it was discovered that the MFCU fuel tube of one of the engines had ruptured (Fig. 1 (a)). The Spanish Air Force reported that two other incidents occurred prior to this incident at 133 and 2755 flight hours (FH), respectively. The tube in the present study had 2864 FH since commissioning and approximately 109 FH since the second failure, which occurred one year earlier and after a change of the entire MFCU. The MFCU scheme, in which the fuel tube pressure control was installed, is shown in Fig. 1 (b). Fig. 1 (c) shows the fuel tube as-received, which was disassembled to remove the end nut.

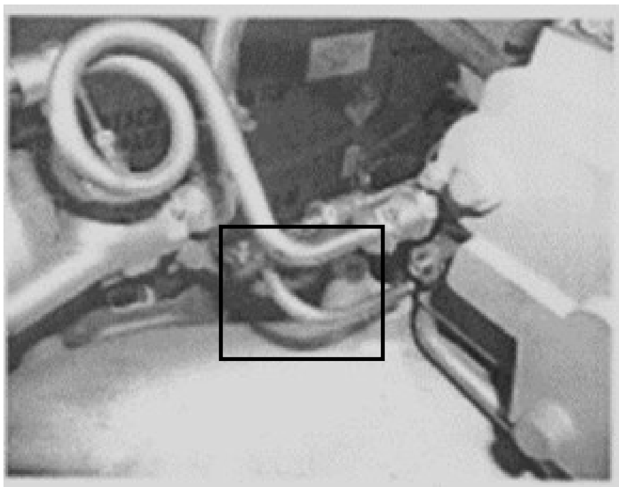

Fig. 1 (a) Attachment location of the failed fuel tube of the aircraft engine MFCU

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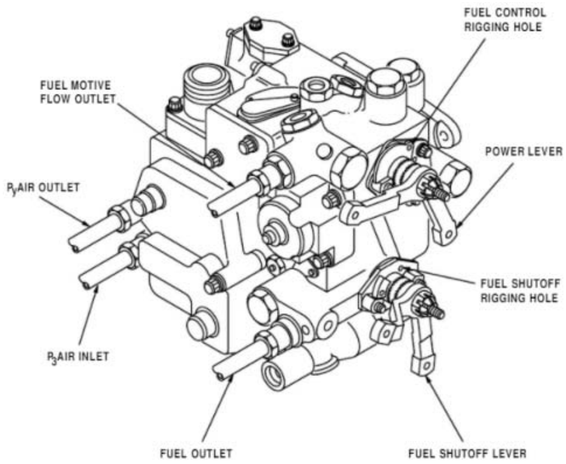


Fig. 1 (b) Scheme of the MFCU where the fuel tube is installed

Fig. 1 (c) general view of the fractured tube as received

The tube was manufactured of X6CrNiTi18-10 (AISI 321) type steel, which is an austenitic stainless steel with good properties such as corrosion resistance, conformability and weldability. Furthermore, this steel, when is stabilized with titanium, shows better behavior against intergranular corrosion and high temperature oxidation. For all these reasons, it has multiple applications, not only in the metal working industry, using them as burners, ovens, tubes and trays, but also in the petrochemical and food processing industry, as in tubes, vessels and piping for nuclear reactor pipelines. This steel is non-magnetic in the annealed state and can only be hardened by cold working [8]. In addition, this type of steel is also used for the manufacture of fuel or coolant pipes in aircraft systems. Due to the numerous similar cases detected, some precautions have already been established in the engine maintenance manual to be taken into account during handling.

II. Materials and Method

The chemical analysis of the tube material, shown in Table I, was carried out using XRF equipment, Panalytical model PW2404, and by fusion and combustion techniques LECO equipment. The composition of the material corresponded to stainless-steel type X6CrNiTi18-10 (AISI 321) (UNE EN 10886-1:2006).

A hardness test was performed on a cross section of the pipe in an area far from the fracture, using a durometer Future FM7 hardness tester, resulting in hardness values shown in Table II.

TABLE I
Chemical Composition (% Weight)

Fe	C	Si	Mn	P	S	Cr	Ni	Mo	Ti	Cu	N
Base	0.03	0.57	1.63	0.024	0.002	17.1	10.2	0.42	0.48	0.30	0.0126

TABLE II
Hardness (HV300 g)

Sample	Hardness (HV_{300g})
Cross section	212 ± 6

The metallographic samples used for microstructural characterization were obtained mounting the areas of interest in conductive resin and, after polishing and etching with superpicral etching agent (10 g picric acid, 5 ml HCl in 100 ml of ethanol), the microstructure was observed under a Leica MEF4M optical microscope.

To observe the fracture surface, a Leica Wild M10 stereo microscope and a Jeol 6500F FESEM equipped with an Oxford energy-dispersive EDX were used.

III. Results and Discussion

A. Visual Observation and Macrofractographic Study

The fracture occurred in a plane of the cross-section that forms a 30° angle with the plane normal to the generatrix. It was located in the vicinity of the connector terminal junction area with the pipe. It exhibited some plastic deformation in diameter and most of the fracture surfaces showed a shiny and soft texture (Fig. 2).

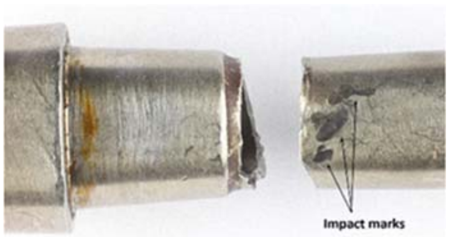


Fig. 2 (a) Side view of the fracture area

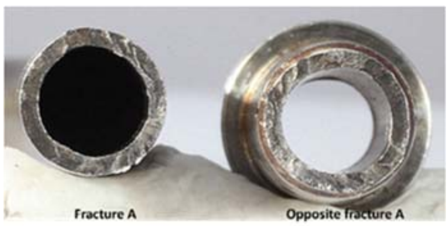


Fig. 2 (b) The fracture surface (A) and its opposite fracture surface

The fracture surface (A) shown in Fig. 2 (b) was inspected and six zones on this surface were selected for more detailed inspections, as shown in Fig. 3.

B. Microstructural Characterization

Two samples were mounted from longitudinal and cross-section area away from the tube fracture and metallographically prepared.

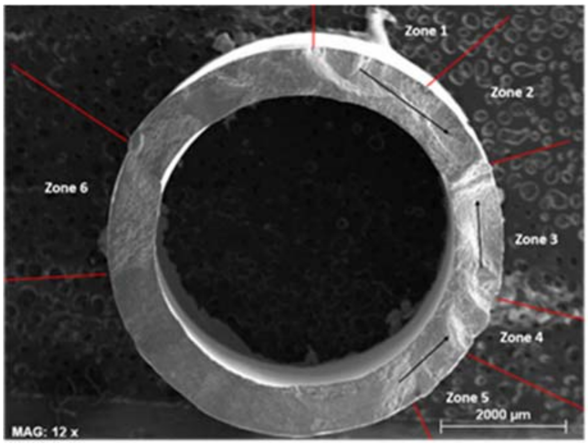


Fig. 3 Front view of the A fracture surface. The black arrows indicate fracture propagation

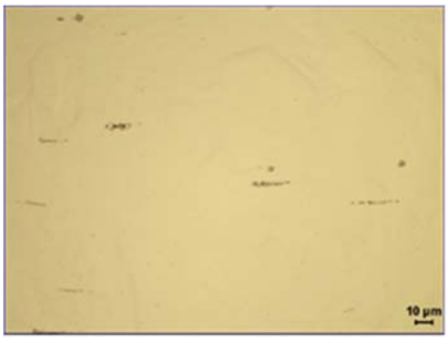


Fig. 4 (a) Carbides and carbonitrides chains aligned in the longitudinal direction of the tube

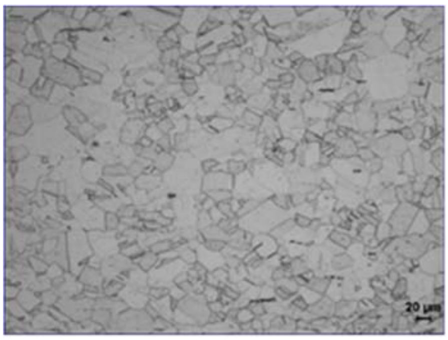
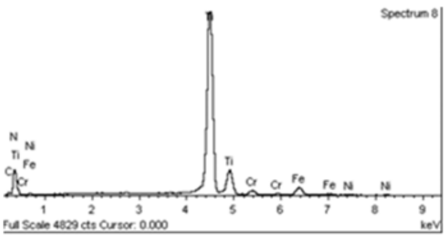


Fig. 4 (b) Austenitic microstructure



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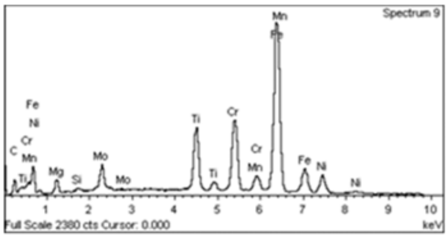

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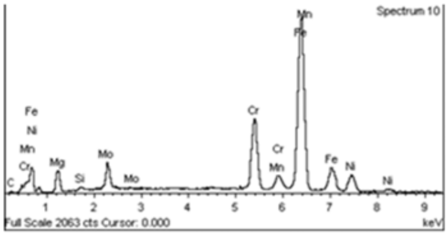


(c)

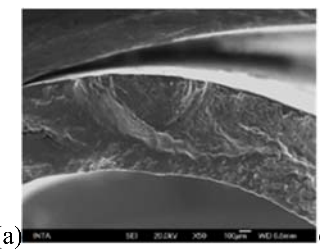
Fig. 5 EDX spectra: (a) Titanium carbonitrides, (b) Titanium and molybdenum carbides, (c) Molybdenum carbides

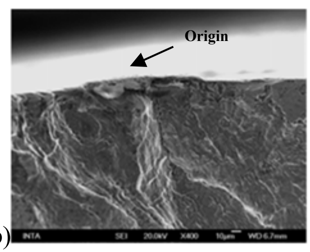
The tube material microstructure (Fig. 4) corresponded to equiaxial austenite grains with titanium carbides and carbonitrides and molybdenum carbides. All particles were analyzed by EDX resulting in the spectra shown in Fig. 5.

C. *Microfractographic Study*

The fracture surface A was first inspected following the black observation line shown in Fig. 3, between zones 1 and 2. The fracture origin was located in zone 1, also showing in this area propagation lines and fatigue striations (Figs. 6 (a)-(d)) also present in zone 2 (Fig. 6 (e)). Some crushed microvoids were identified, indicating an overload fracture, Fig. 6 (f). Subsequently, another observation line was followed between zones 3 and 5, verifying the existence of another crack whose origin was located in zone 5, although it could not be identified because in this zone there were multiple crushes and it was highly oxidized. Fatigue striations were observed in zone 4 and some crushed microvoids in zone 3, Fig. 7. Due to the multiple crushing in zone 6, no microfractographic features could be identified. A surface with multiple defects and marks was observed on the outer wall surface of the tube near zone 1 (Fig. 8).

In this study, at least two crack origins were located. In both cases, fatigue striations, typical of a progressive fracture, were observed, leading to a final fracture by static overload.

(a) 

(b) 

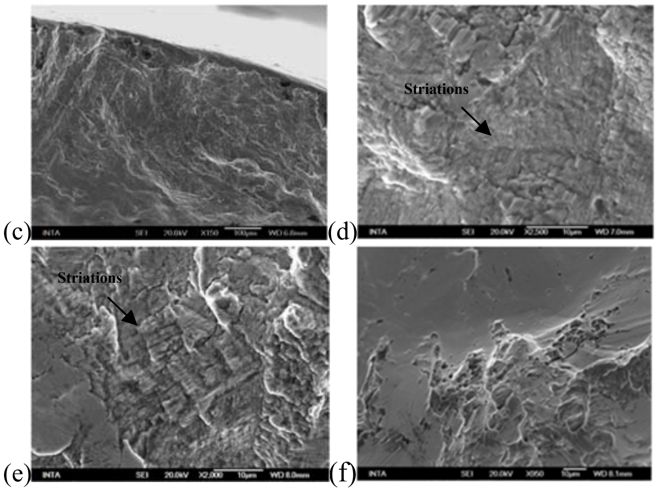


Fig. 6 (a) Zone 1. Overview of the crack origin in fracture A, (b) Fracture origin, (c) Fracture propagation zone, (d) Fatigue striations, (e) Zone 2. Fatigue striations, (f) Crushed microvoids

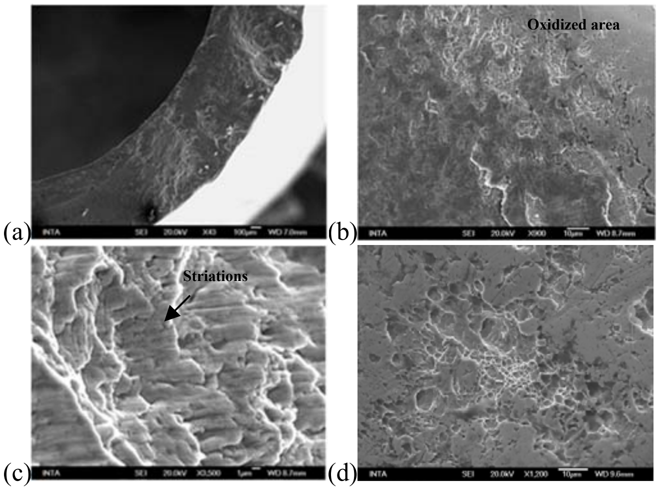


Fig. 7 (a) Zone 5. Overview of the crack origin in fracture A, (b) Oxidized zone, (c) Zone 4. Fatigue striations, (d) Zone 3. Crushed microvoids

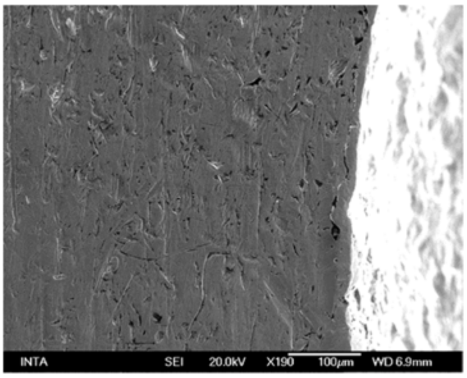


Fig. 8 Zone 1. Multiple defects on the surface

The fracture mechanism was fatigue, which could have originated from the multiple defects observed on the external surface of the pipe and where the cracks could have progressed due to the vibrations to which the pipe was subjected.

D.Fracture Profile

In order to analyze the fracture surface grains in the zone 1, a longitudinal section of the opposite fracture surface was mounted and etched to reveal the grain crystallinity. Fig. 9 shows that the fracture exhibited a transgranular profile.

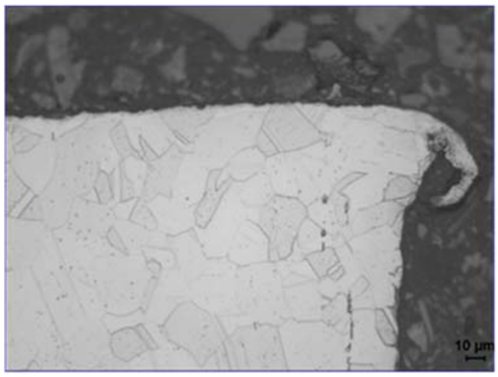


Fig. 9 Transgranular profile of the opposite fracture surface. Zone 1

E. Fracture Factors and Recommendations

In the light of the results obtained, the possible factors that could have triggered the fatigue mechanism would be vibrations and stresses introduced during the tube assembly.

Regarding the stresses introduced during the tube assembly, it was recommended that the tightening of the tube end nuts should be done at the same time, to avoid misalignment of the tube ends with their housings, which could lead stresses. Considering the handling of tube as a critical stage, the tightening sequence of the tube ends should be established in the maintenance manual of the engine aircraft. And, in the event that this maintenance manual does not establish any type of inspection of the tube assembly, it would be advisable to perform different visual inspections and penetrate testing.

To absorb vibrations, it was recommended to install clamping flanges surrounding the tube with some type of elastomeric material.

IV. Conclusion

An aircraft fuel injection pipe, manufactured in X6CrNiTi18-10 stainless steel according to the standard UNE EN 10886-1 and presenting an austenitic microstructure, with a hardness value of 212 HV_{300g}, corresponding to a state of thermal annealing treatment, suffered a fracture in service.

Macro and microfractographic features revealed that the fracture of pipe was produced by fatigue mechanism, probably as a consequence of the vibrations to which it has been subjected. At least two fracture origins were located, one on the outer wall of the pipe, where an incorrect surface finished was observed, leading to a final fracture by static overload. In addition, stresses introduced during the pipe assembly could also have contributed to the fracture.

Although the type of the steel and its state of treatment were suitable for the application in which it had been used, incorrect tightening torque or non-installation of clamping flanges to absorb the engine vibrations could have caused cracks, incubated in surface defects, and thus propagate through a fatigue mechanism until reaching the final fracture. Therefore, some recommendations were made to avoid factors that facilitate the fracture, such as inspections at the tube assembly stage or surrounding the tube with clamping flanges made of some type of elastomeric material.

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