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Fatigue strength of tungsten inert gas-repaired weld joints in airplane critical structures

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ABSTRACT

In this work the effect of Gas Tungsten Arc Welding (GTAW) repairs on the axial fatigue strength of an AISI 4130 steel welded joint used in airframe critical to the flight-safety was investigated. Fatigue tests were performed at room temperature on 0.89 mm thick hot-rolled plates with constant amplitude and load ratio of $R = 0.1$, at 20 Hz frequency. Monotonic tensile tests, optical metallography and microhardness, residual stress and weld geometric factors measurements were also performed. The fatigue strength decreased with the number of GTAW repairs, and was related to microstructural and microhardness changes, as well as residual stress field and weld profile geometry factors, which gave origin to high stress concentration at the weld toe.

1. Introduction

Flight-safety has been the main area of concern for aeronautic authorities since the introduction of the first airplanes. One critical factor that aeronautical design must take into account is the difficulty of transporting load against gravity force during take-off and efficiently discharges it with minimum cost and maximum safety because failures in any of these stages can produce catastrophic accidents that often include loss of human lives (Godefroid, 1993). Since the catastrophic accidents with the English "Comet" airliner in the 1950s, the fatigue process has been the most important focus and operational consideration for both civil and military aircrafts (Goranson, 1993; Schijve, 2009). At present, in spite of the vast amount of experimental data generated in the last sixty years, fatigue failures still correspond to about 60% of the total failures in aircraft components (Findlay and Harrison, 2002; Bhaumik et al., 2008). This demonstrates the significance and complexity of the structural fatigue process and the importance of studying any aspects that would affect the frame structure of aircrafts.

Many fractures of aircraft materials are caused by fatigue as consequence of inadequate design and any kind of notch (stress concentrations) produced during manufacture or maintenance operations. Bhaumik et al. (2008) mentioned that failures in aircraft components can be due to a variety of reasons: (i) complex stress cycles, (ii) engineering design, (iii) manufacturing and inspection, (iv) service and environmental conditions, and (v) properties of the material. These authors also mentioned that the potential sources of fatigue failures can be related to one or more of the following errors: (i) design, (ii) manufacturing, (iii) assembly, (iv) inspection, (v) operation, and (vi) maintenance. In the same way, Goranson (1993), Wenner and Drury (2000) and Latorella and Prabhu (2000) mentioned that the structural failures during flight are usually attributed to fatigue of materials, design errors and aerodynamic overloads. Carpenter (2001) and Koski et al. (2006) further highlighted that due to the high number of older aircrafts that are flying nowadays, problems such as stress corrosion cracking, corrosion-fatigue (separately or simultaneously) and wear are also expected to occur. The understanding of all these issues demands extensive money and time investment, planning, research and development on maintenance and repair welding procedures toward assuring the safe and continued airworthiness of aircrafts.

The present study has helped demonstrate that the problem of fatigue failures is more complex and dangerous if an aircraft contains welded structures. Numerous difficulties that require con-

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sideration in evaluating and defining potential fatigue failures in welded structures have been determined as follows (Atzori et al., 2009):

- defining material properties which vary throughout the weld joint – weld metal (WM) and the heat affected zone (HAZ);
- presence of high residual stresses, both local (due to the weld itself) and structural (due to the assembly process of the structure) which also vary throughout the weld joint;
- defining precisely the weld bead geometry (bead size and shape) and radius at the toe of the weld, that vary even in well-controlled manufacturing and are the most important factors affecting the design and engineering of welded aircraft structures.

According to Aloraier et al. (2010), the weld toe cracking is caused by the weld metal that has higher yield strength and tensile strength than the parent metal (weld strength overmatch). These authors commented that "when the weld area shrinks on cooling from the welding temperature, cracking occurs in the heat-affected zone (HAZ) of the steel because the yield and strength levels of the HAZ are lower than those of the weld metal". Additionally, it is commented that "the toe region is highly susceptible to fatigue cracking due to the presence of weld defects, stress concentration due to toe geometry and adverse metallurgical conditions such as tensile residual stresses and coarse HAZ microstructure".

The presence of a tensile residual stress field and weld defects, such as slag inclusion at weld toe, undercut, lack of penetration and misalignment, is many times found in welded joints and effectively reduce the fatigue crack initiation phase. Wahab and Alam (2004) mentioned that the crack propagation stage was 75–89% of the total fatigue life for all types of welded joints tested, so that the entire life may be assumed to be dominated by crack propagation. These authors highlighted that in order to justify the integrity of welded structures, it is necessary to estimate the fatigue life of welded joints containing defects and to compare the obtained result with the required operational life that would be required for the aircraft.

In addition, welded aeronautic structures accumulate weld repairs which are carried out during the manufacturing and the operational life of aircraft. The size and frequency of defects depends on the welding process, welding procedure, geometry of the weld, ease of access to the place to be welded and care took during the welding (Wahab and Alam, 2004). In most cases, such defects are difficult and costly to detect and define nondestructively (Wahab and Alam, 2004). Repair welding is often carried out in situ with difficulty of access, without preheating and post weld heat treatment and without inspection (Lant et al., 2001).

Although efforts to improve the repair welding procedure for defective and degraded components have been extensive in the last decade, few papers have been written on this subject. Moreover, the great majority of them are about aged and degenerated metals in petrochemical and offshore industries and power plants (viz., Aloraier et al., 2010; Branza et al., 2009; Vega et al., 2008; Mirzaee-Sisan et al., 2007; Edwards et al., 2005; Lant et al., 2001). Additionally, most of the carried out studies are based on simulation by finite element method – FEM – (e.g., Sharples et al., 2005; Sun et al., 2005; Dong et al., 2005; Aloraier et al., 2004; Hyde et al., 2004). Consequently, there are only few studies about multiple repair welding operations (e.g., Vega et al., 2008).

Because repair welding is a necessary and frequently used procedure, one can conclude that the availability of experimental data about their effects on the structural integrity of aircrafts would be very important and useful. In this way, this would also help to determine effective inspection intervals of high-responsibility/critical components and to assess and assure the potential flight-safety of welded structures.

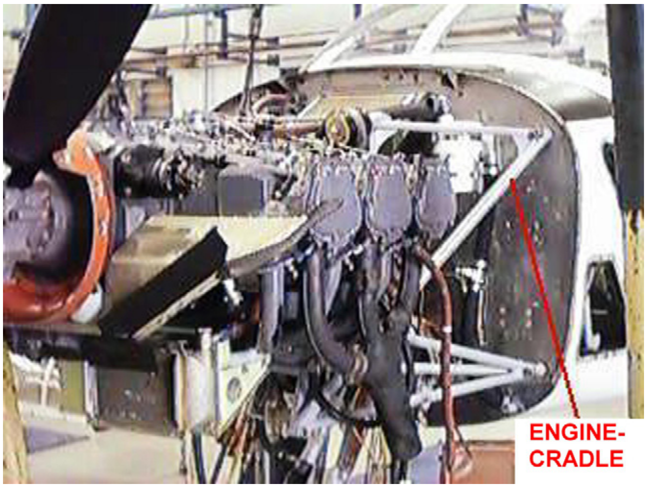

Fig. 1. Engine-cradle assembly in a Brazilian T-25 Universal aircraft.

In some aircraft models (e.g., agricultural, military training and acrobatic), the most repaired component is the one that supports the motor, called "engine-cradle" (Fig. 1). This component presents a geometrically complex structure made of AISI 4130 tubular steel of many different dimensions and TIG welded in several angles. In the Brazilian T-25 Universal aircraft, for example, besides supporting the motor at an extremity (correct balance), the engine-cradle also maintains the nose landing gear fixed at another extremity.

Because the engine-cradle is a component critical to flight-safety, the aeronautic standards are extremely rigorous in its manufacturing, imposing a "zero-defect index" to the quality of the welded joint. Consequently, this structure is 100% inspected by non-destructive testing (NDT). Importantly, these welded engine-cradle structures are frequently subjected to several repair welding operations during manufacture, so that they have to be in strict compliance to current standards ("zero-defect index"). As a consequence, even though approved by NDT during manufacture, these components may present a historic record of repair welding operations whose effects on the microstructure, mechanical properties and structural integrity are unknown.

This subject becomes even more complex when taking into account the additional historic record of repair welding operations during the service life of the aircraft (maintenance repair welding). For example, an investigation on 157 engine-cradle failure reports of Brazilian T-25 Universal aircrafts indicated that all failures occurred at welded joints as a result of fatigue cracks. As a consequence of these successive repair welding operations, the interval between inspections ("Time-Before-Fail") was reduced from 4000 h to 50 h of flight (Nascimento, 2004). Motivated by the high failure incidence on this component, an extensive research program to evaluate the effects of the repair welding on its structural integrity, mechanical properties and microstructure has been developed. The question that needed to be answered was: how many times can a welded joint be safely repaired by welding? The work described in this paper addressed the lack of data and analysis on this crucial subject.

Based on experimental results, the aim of this study was to investigate the effects of successive GTAW repairs on the axial fatigue strength of welded joints of AISI 4130 hot-rolled steel plates, 0.89 mm thick. Special emphasis was given to a commonly employed maintenance repair welding procedure, used during the operational life of aircrafts and characterized by overlapping the defective or fractured weld bead. The results obtained can contribute to an in-depth understanding on the subject as well as, to