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Fatigue in laser welded titanium tubes intended for use in aircraft pneumatic systems

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ABSTRACT

The pneumatic system conducts the pressurized hot air from the engine to the environmental systems of the aircrafts. In-service failures of arc-welded pneumatic parts have driven further developments of laser beam welding as an alternative method. Here, a fiber laser with 2 kW power had been employed to weld commercial purity titanium tubes with 0.5 mm wall thickness and 50 mm diameter. For comparison purposes, semiautomatic TIG welding was realized. The chosen parameters speed and laser power for laser welding were 200 W–2 m/min and 250 W–3 m/min. The laser welded tubes presented 1 mm wide weld beads composed by partially twinned α-Ti grains. The TIG welded tubes showed 5 mm wide beads composed by acicular α-grains. These observed differences had been associated with the cooling rates, which are ten times higher in the laser case. Both laser and TIG welded tubes were cycled 44,000 times in a pneumatic bench at 350 °C without failures or cracks that could release the internal pressure. After the pressurization tests, the tubes were tested for tensile and fatigue resistance. The yield stresses, tensile strengths and total elongation did not change comparing base material, TIG welded and laser welded cases. The condition 200 W–2 m/min presented superior fatigue resistance values compared to other welding conditions, and could be considered similar to the tubes in the unwelded condition. The microstructural and mechanical results had shown that the current laser technology can replace, with advantages, the arc welding for the joining of the titanium tubes.

1. Introduction

An important power source in commercial aircrafts is the high pressure hot air bled from the engines and channeled throughout the airframe to the secondary systems. This hot air is transported through the engine bleed system, i.e. a set of ducts containing curved and straight sections, joints, welded parts, valves and sensors [21,22]. Among the various materials suited for the use in this system, titanium stands out because of its favorable characteristics. Similarly to other light weight metals such as aluminum and magnesium, titanium and its alloys show a high strength to specific mass ratio. In addition, titanium presents very good corrosion resistance, acceptable weldability and operational temperatures well above aluminum [9,10]. For example, the tensile strength of titanium alloys can reach 1300 MPa depending on the alloying elements and the heat treatment [7].

Although titanium has been successfully used in the pneumatic system, a number of in-flight failures of the ducts have been reported in literature [1,16]. The arc welded titanium tubes are occasionally susceptible to fatigue cracking during aircraft service. The failure propensity by thermo-mechanical cycling doesn't mean that there are recurring failures of this system. However, one should consider this possibility before an accident occurs, which could lead to the aircraft crash with human and material losses.

Some analyses were carried out in broken T-type ducts made of pure Ti class A40 with 50 mm in diameter and 0.52 mm in thickness [1]. These tubes were Tungsten Inert Gas (TIG) welded and it is suggested that the cracks had initiated at multiple spots around the inner surface. Cracks also occurred after cyclic pressurization during service life until the occurrence of high stress concentrators, causing a reduced lifetime of the components [1].

Lynch et al. [16] also reported failures in grade 3 titanium tubes of 150 and 180 mm diameter, after welding by TIG process. These tubes usually failed after 26,600 h, equivalent to 19,275 pressurization cycles. The microstructural analyses indicated that the service failures originated in the heat affected zone (HAZ), which had a

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Nomenclature

AR	as received
AW	as welded
BM	base material
FZ	fusion zone
HAZ	heat affected zone
HV	Vickers Hardness
ICDD	International Center for Diffraction Data
LBW	Laser Beam Welding
SEM	scanning electron microscopy
TIG	Tungsten Inert Gas
WB	workbench cycled
XRD	X-ray diffraction
b	slope parameter of Weibull distribution (Weibull modulus)
N_r	reliable life for a reliability of r%
r	probability of survival in percentage
ε_u	elongation to fracture observed in tensile test
$\sigma+$	maximum von Mises residual stress at the welded joint
$\sigma-$	minimum von Mises residual stress at the welded joint
σ_{ef}	effective Mises stress
σ_u	ultimate tensile strength
σ_y	yield stress
θ	scale parameter of Weibull distribution

coarse acicular alpha structure contaminated by oxygen. The TIG welding process produced an extended and brittle HAZ. Since the process was manual, the welding speed was low, and the heat input was thus high. The occurrence of these failures opens the possibility of studying the application of alternative welding processes such as Laser Beam Welding (LBW). This process offers the possibility to reduce the heat-affected zone and the residual stresses by a strictly controlled heat input.

The fatigue strength of titanium and other light metal alloys welded by laser or arc welding processes has been studied in recent literature [13,7,18,11]. The studies are focused on practical applications of welding technology and on the design of welded parts. Roggensack et al. [20] investigated two different methods of welding, laser and plasma. In this study, no significant differences were found on the fatigue behavior of titanium parts welded by these methods. However, extreme loads led to earlier fatigue failure in the plasma-welded specimens. Casavola et al. [7] verified by means of fatigue tests carried out in twelve LBW specimens that the fatigue failures in grade 2 and grade 5 titanium occurred far from the weld location in eleven of twelve occasions. These unexpected results were related firstly to the limited extent of the heat-affected zones as well as to the small dimensions of the resolidified grains. Secondly the LBW joints were not misaligned, reducing unexpected shear stresses. Thirdly, the welding seam profile was fairly regular and the stress concentration factor was quite small. Li et al. [14] welded CP-Ti of 1.5 mm in thickness by hybrid fiber laser plus TIG welding. The authors' results had shown that excellent welds can be produced by the hybrid process due to complimentary benefits of both processes, such as gap bridging capability and high productivity.

One of the most important issues in titanium welding is the N_2/O_2 contamination of the liquid pool by atmospheric air. This contamination leads to high joint brittleness with associated poor toughness of the welded part [15]. It is reported that oxygen and nitrogen in the weld bead induce the formation of interstitial solid solution, in which the O and N occupy the octahedral interstices of the compact hexagonal crystal structure of titanium, expanding the lattice parameters [10]. Thus, there is an increase in c/a ratio that also increases the hardness. Hongyan et al. [12] explained the effect of hardening caused by an increase in c/a ratio by reducing the number of slip planes, since titanium is deformed mainly by the sliding of pyramidal and prismatic planes with c/a ratio below ideal.

Many studies did not produce valuable results because the fatigue tests were conducted far from the actual pressurization parameters of the different aircraft operational stages. In a previous work [6], titanium ducts welded by the TIG process were submitted to cyclic pressurization tests at controlled temperature in order to reproduce aircraft service conditions. These simulation tests were conducted in a pneumatic workbench and were aimed at the evaluation of the aging conditions on the tensile and fatigue properties of the tubes. The fractographic analysis of a failed duct revealed that fatigue cracks can nucleate in the vicinities of weld flaws and gradually propagate through the wall, indicating that an improvement of the welding process is necessary. This work will explore further the reliability of the titanium tubes after the service lifetime. This work intends to understand the effect of different weld sources and parameters on the microstructure and mechanical behavior of the titanium tubes of an aircraft pneumatic system.

2. Material and methods

The base material (BM) was thin-walled grade 2 commercial pure Ti tubes, similar to those employed in the pneumatic system of a commercial airplane. The chemical composition of the material is given in Table 1. The maximum oxygen content of 0.25% is responsible for the increase in strength, when compared with the grade 1 CP-Ti. The microstructure, as depicted in Fig. 1, consisted of α-phase equiaxed grains with an average grain size of 20 μm [4]. The specimen dimensions are the following: external diameter = 50 mm, wall thickness = 0.05 mm and tube length = 300 mm. The specimens were previously annealed for stress relief at 560 °C per 150 min. Table 2 shows some of the mechanical properties of the tubes being σ_y and σ_u the yield and ultimate tensile stresses, ε_u the total elongation and HV the Vickers Hardness [5].

The titanium tubes were bead-on-plate welded in the longitudinal direction without filler metal (autogenously). Since titanium is a prone-to-burn metal during melting, a special arrangement was used to protect both upper and bottom surfaces of the welds. Firstly a nozzle with a tailor-made configuration protected the weld at the external tube surface. This nozzle encapsulated the welding region and surroundings with a laminar argon flow all though the welding process. The root of the weld was protected as well by pressurizing the tube. To accomplish this, both sides of the tube were partially sealed, and one side had a gas nozzle and the other extremity had a tiny hole in order to produce a positive inert gas pressure. Two welding processes were employed in this study: the conventional Tungsten Inert Gas Welding (TIG),

Table 1
Chemical composition of CP-Ti (wt.%).

C	O_{max}	Fe	N	H	Other elements	Ti
0.10	0.25	0.20	0.05	0.015	0.15	Balance