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HIGH TEMPERATURE PNEUMATIC FATIGUE TESTING OF THIN-WALLED TITANIUM DUCTS

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Abstract. *An important energy source in commercial aircrafts is the high pressure, high temperature air that is bled from the engines and routed throughout the airframe to secondary systems. This hot air is transported by the engine bleed system, a set of thin-walled ducts whose reliability and durability are important for flight safety. Among the various materials suited for use in this system, titanium stands out because of its favorable characteristics, such as high strength-to-weight ratio and corrosion resistance. The effects of aging must be taken in account when predicting the useful life of the bleed system parts. In order to provide information concerned with the performance of these ducts, a pneumatic workbench capable of simulating the temperature (300°C) and pressure (up to 250 psi) cycles found in flight conditions was built and employed in cyclic pressurization tests (frequency = 0.5 Hz) of titanium duct samples. The test-pieces were designed to show all of the bleed ducts' genuine characteristics, including curved and straight sections, cold drawn parts and welded connections. Tensile and fatigue tests were further conducted with ring-shaped specimens taken from the cycled ducts. Fracture analyses via SEM were also performed. The obtained results are part of a research project aimed at understanding and describing the in-service damage process suffered by the ducts.*

Keywords: *pneumatic systems, titanium ducts, fatigue.*

1. INTRODUCTION

Among the various metallic materials suited for use in pneumatic systems of aircrafts, titanium stands out because of its favorable characteristics, such as high strength-to-weight ratio, corrosion resistance, good formability and appropriate mechanical properties. Commercially pure titanium is indicated for application in the air distribution lines, where the operating temperatures can reach 300°C. A number of in-flight failures of titanium pneumatic ducts, all of them associated with cracking adjacent to welds, have been described in technical literature (Lynch, 1995; Barta, 1988). The investigations lead to conflictant conclusions upon the failure causes, pointing out the embrittlement due to migration of hydrogen to the weld zone in the presence of residual stresses or the crack growth occurring mainly by fatigue from pre-existing cracks. The understanding of the damage evolution during service conditions is of great importance to the improvement of the design and fabrication of pneumatic system components using titanium.

Pure titanium has a hexagonal close-packed structure with a *c/a* ratio of 1.587, which is lower than the ideal *c/a* ratio (1.633), and is strongly plastically anisotropic at room temperature due to texture and the wide variety of deformation mechanisms (Salem et al., 2003; Balasubramanian and Anand, 2002). In hcp materials, the most common slip modes are $\{10\bar{1}0\}\langle 11\bar{2}0\rangle$, $\{10\bar{1}1\}\langle 11\bar{2}0\rangle$ and $\{0001\}\langle 11\bar{2}0\rangle$. They constitute a total of four independent slip systems. In pure titanium, the slip occurs most easily by the activation of dislocations with <a> type Burgers vector on prismatic planes, and to some extent on basal and pyramidal planes. Since the <a> slip alone cannot provide five independent slip systems, deformation by <*c*+*a*> slip or by twin systems must be activated in addition to <a> slip in order to maintain the compatibility of polycrystalline deformation (Balasubramanian and Anand, 2002).

At the macroscopic level, the deformation mechanisms associated with plastic deformations of commercially pure titanium are strongly dependent on the temperature and strain rate. Deformation by slip occurs predominantly on a $\{10\bar{1}0\}$ plane in a $\langle 11\bar{2}0\rangle$ direction over a wide range of temperatures with secondary slip more prevalent at higher temperatures. Besides, the cross slip of <*c*+*a*> dislocations from the $(1\bar{1}00)$ plane to the $(11\bar{2}2)$ or $(10\bar{1}1)$ plane becomes energetically favorable above 300ºC. Deformation by twinning has been observed at low temperatures and the density of twins increases with increasing strain rate, strain and decreasing temperature (Chichili et al., 1998; Yoo et al., 2001). Twinning has been reported occurring on the $\{10\bar{1}1\}$, $\{10\bar{1}2\}$, $\{11\bar{2}1\}$, $\{11\bar{2}2\}$, $\{11\bar{2}3\}$ and $\{11\bar{2}4\}$ planes (Xiaoli and Haicheng, 1996).

The effects of aging in aircraft parts and the in-service changes in the mechanical properties under different stress-temperature regimes are related to these complex deformation mechanisms and the high reactivity of titanium with interstitial elements (oxygen, carbon, nitrogen and hydrogen). The affinity of titanium for oxygen is one of the main factors that limit its application as structural material at high temperatures. The absorbed oxygen combines chemically with titanium to form a hard and brittle oxide layer on the material's surface. This oxidized scale of very complex structure can be composed of a set of parallel layers, containing several distinct oxides (Bertini et al., 1980; Pitt and Ramulu, 2004). The mass increase of titanium exposed at high temperatures can be assumed to be due to the diffusion of oxygen. Additionally, diffusion within the grain increases faster than grain boundary diffusion as the temperature increases. At lower temperatures grain boundary diffusion becomes more influential (Bertini et al., 1980; Fukuzuka et al., 1980).

The effects of the interstitial elements (C, O, N) on mechanical properties of titanium can be summarized as follows. Like most impurities in metals, they have certain virtues and certain drawbacks. Small amounts of these interstitials offer a substantial strengthening together with little loss in tensile ductility at room temperature. They increase the strain-rate sensitivity, produce yield-point phenomena and the dynamic strain-aging caused by the interaction between moving dislocation and mobile points defects. They lose their strengthening effect at elevated temperatures, but at subzero temperature promote embrittlement and have a deleterious effect on toughness, weld ductility, machinability (Salem et al., 2003; Chichili et al., 1998; Bertini et al., 1980; Nemat-Nasser et al., 1999). However, the improvement in static strength rarely results in comparable improvements in fatigue properties and is usually accompanied by loss in fracture toughness and in greater susceptibility to environment-induced cracking (Wanhill, 1977). In combination with hydrogen, their detrimental effects can be magnified. In this case, hydrogen embrittlement of metals used in aircraft components can cause serious deterioration of their mechanical properties. Especially vulnerable are the titanium tubular ducts which are exposed to high temperatures and pressures. This is a type of deterioration that can be linked to corrosion as it involves the ingress of hydrogen into a component, and can seriously reduce the ductility and load-bearing capacity, which causes cracking and catastrophic brittle failures (Barta et al., 1988; Hack and Leverant, 1982; Hardie and Ouyang, 1999). Eventually, the oxide film formed by thermal oxidation of titanium can prevent corrosion and hydrogen absorption (Fukuzuka et al., 1980). Experimentally, it is observed that deformation twinning can effectively strengthen a material under some circumstances and weaken it in others (Salem et al., 2003; Chichili et al., 1998; Nemat-Nasser et al., 1999). Besides, deformation twinning plays an important role in maintaining a generalized plastic flow and also in mechanical behavior of titanium at all temperatures.

High-cycle and low-cycle emerged as the most common fatigue failure modes. Thus, stress-life and strain-life approaches were revealed as being of key importance in the design process, particularly for the automotive and aerospace sectors. Stress concentrations combined with geometry irregularities arose as the most important design factors affecting fatigue. On the other hand, the critical manufacturing dependent factor is the presence of residual stresses imparted through many production process such as machining, casting and surface engineering processes (Darlington and Booker, 2006). However, fatigue cracking of pure titanium is a complex phenomenon, because it is affected by texture, grain size, strain amplitude and temperature. The fatigue limit of titanium increases as the interstitial content rises and as the grain size and temperature decrease. The oxygen alloying favors fatigue performance. Nevertheless, fatigue strengths are generally higher at low temperatures because of thermally limited slip generation and an increased tendency towards twinning. The fatigue strength of titanium increases also at low hydrogen concentrations. Higher hydrogen contents reduced the fatigue life as a result of the formation and fracture of brittle hydrides (Wasz et al., 1996).

Previous studies suggested that mechanical twinning appears to play an important role in the fatigue behavior of titanium. Along the $\{11\bar{2}2\}$ twin boundaries, extrusions were observed during fatigue. Twins of the $\{11\bar{2}1\}$ type formed during cyclic loading exhibited permanent damage at the twin-matrix interface. However, slip bands in the grains with favorable crystallographic orientations for slip induced to holes and cavities along slip plane $\{10\bar{1}0\}$, which is believed the embryo of microcracks (Xiaoli and Haicheng, 1996). This competitive role of twinning against cracking depends closely on the character of the material, experimental conditions and defect properties (Yoo, 1981).

The cumulative character of the process of fatigue damage and failure is connected with the localized plastic deformation, which is conditioned by the movement and generation of dislocations and their interaction with other dislocations and obstacles to their movement (Puškár and Golovin, 1985). In titanium, a different type of dislocation configuration exists in each grain and it is uncommon to observe cell structures formed around a fatigue crack. When they are formed, cell structures would not develop so well as have been observed in fcc and bcc metals. This suggests that the mode of fatigue crack propagation is strongly affected by grain orientation. Therefore, the fatigue crack propagation causes a striking difference in intensity and nature of deformation along the crack itself. Besides, the cracks propagation rate is not steady in a grain, but varies depending on metallurgical conditions (Sugano and Saito, 1980).

The high temperature environment can substantially influence the common sequence of fatigue crack initiation, crack growth and final fracture. This fact is related to the additional damage mechanisms, which are encountered at elevated temperature. The cyclic loads can accentuate the time-dependent damage and environmental effects (Sadananda and Vasudevan, 1997; Puškár and Golovin, 1985). Measurements of fatigue life at room temperature simultaneously with study of internal structure of the material, type damage, and final fracture can reveal numerous features common to the fatigue behavior of metallic materials.

In order to provide information concerned with the service performance of the titanium ducts in aircrafts, a pneumatic workbench capable of simulating the temperature (300°C) and pressure (up to 250 psi) cycles found in flight conditions was built and employed in cyclic pressurization tests (frequency = 0.5 Hz) of duct samples. The test-pieces were designed to show all of the bleed ducts' genuine characteristics, including curved and straight sections, cold drawn parts and welded connections. After the cyclic pressurization tests, the specimens were cut into several parts so that material samples for mechanical, microstructural, chemical and internal surface analyses were obtained. In the present work, preliminary results concerning the mechanical properties of the pressurized ducts are presented. Tensile and fatigue tests were conducted using ring-shaped specimens. Fracture analyses via SEM were also performed.

2. EXPERIMENTAL DEVELOPMENT

The material and methods employed in this research work are described in the next sections.

2.1. Material

Commercially pure titanium (Ti A40) samples, suited for use in aircraft pneumatic systems, were tested in this work. The material was received as thin-walled tubes (diameter = 50.8 mm; thickness = 0.71 mm), which were heat treated for stress relief (560°C / 150 min) according to MIL H 81200B Standard prior to the fabrication of the test pieces. The chemical composition of Ti A40 is given in Tab. 1 and its microstructure, shown in Fig. 1, is basically formed by equiaxed α grains with an average grain size of 15 μm. The tubular test pieces, see Fig. 2, were designed to contain several of the features found in aircraft pneumatic duct components, such as straight sections, joints, welds and cold-drawn parts.

Table 1. Chemical composition of Ti A40 (wt. %).

Element	C	O	Fe	N	H	Ti
Amount (%)	0.10	0.25	0.20	0.05	0.015	Remaining

Figure 1. Optical micrograph of Ti A40 in the stress relieved condition (500 ×)

2.2. Cyclic pressurization tests

In order to simulate the service conditions of aircraft pneumatic systems, the test pieces were subjected to cyclic pressurization tests at controlled temperature. To do so, a pneumatic workbench composed by a piston compressor, an air-treatment device, and a programmable high-pressure unit, designed and built according to Fig. 3, was used together a tube furnace also produced especially for this work. This workbench is aimed to test different materials for use in aircraft duct components, having a pressure capacity of 300 psi and operating pressures up to 800°C. The flight cycle data obtained from a commercial aircraft were analyzed using the rainflow cycle counting method in order to establish the laboratory test parameters. The pressurization tests of the titanium ducts presented in this work were conducted at

300 and 400°C, with constant amplitude cycles having a pressure ratio (min. / max.) of 0.1 and frequency of 0.5 Hz. At this stage of the research, two maximum pressure values were tested: 250 and 150 psi, both of them with a number of pressurization cycles of 3.4×10^4, which corresponds to approximately 50% of the expected life of the components. The photographs presented in Fig. 4 show a general view of the workbench (Fig. 4a) and the titanium test piece inserted in the opened furnace (Fig. 4b) during the preparation for a pressurization test.

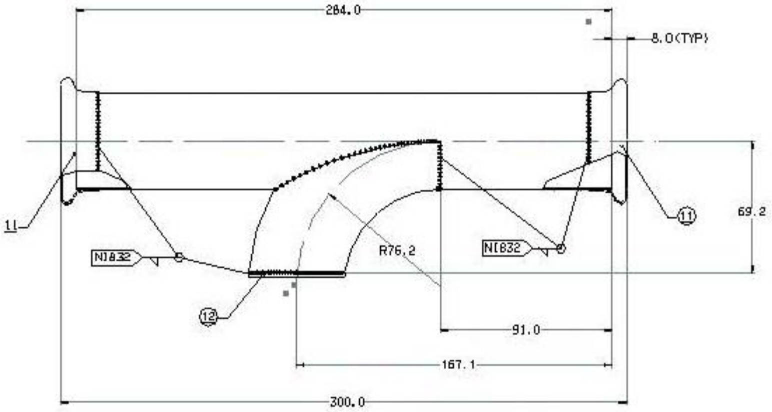


Figure 2. Tubular test piece employed in this work (wall thickness = 0.72 mm)

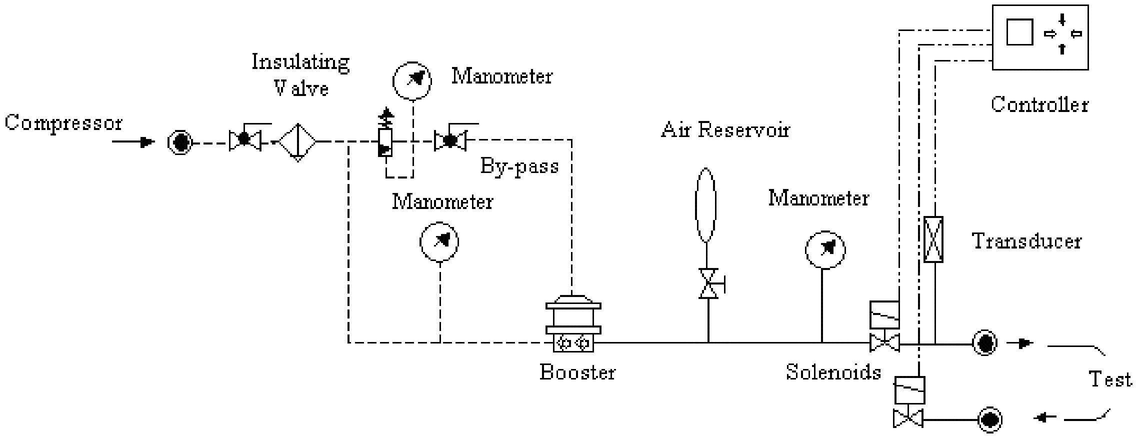


Figure 3. Scheme of the pneumatic workbench employed in the cyclic pressurization tests


(a) *(b)*

Figure 4. Pneumatic workbench: *(a)* general view; *(b)* detail of the test piece inserted in furnace

2.3. Characterization of the fatigued titanium ducts

After the cyclic pressurization tests, the specimens were cut into several parts so that material samples for mechanical, microstructural, chemical and internal surface analyses were obtained. In the present work, the results concerning the mechanical properties are emphasized. The various material conditions are specified as follows: SR (stress relieved), TD00 (untested test piece) and TDXXX-YYY, where XXX = 150 or 250 and refers to the maximum pressure (psi) and YYY = 300 or 400 is the temperature (°C) adopted in the pressurization tests.

The mechanical properties of Ti A40 after the pressurization tests were evaluated by means of tensile and fatigue tests conducted in a MTS servo-hydraulic machine at room temperature in laboratory air. Ring-shaped specimens were cut from the straight sections of the tubular test pieces. A test rig designed and built especially for these tests was mounted in fracture mechanics grips, as shown in Fig. 5*a*. In such a test configuration, the material is loaded in the same direction of the highest principal stress due to the duct pressurization. The ring's width was 10 mm and the gripping setup provided also 10 mm as the initial gage length on each side of the specimen. Figure 5*b* shows an untested tensile specimen besides a tested one. The specimens fractured at one of the two gage length regions. Only the fractured region was considered in the assessment of the elongation. In the case of the fatigue tests, the ring-shaped specimens had a continuous radius which gave them a hourglass profile, as shown in Fig. 5*c*. The outer surfaces of the specimens, together with their edges, were carefully ground with emery paper, while the internal surface was left in its original condition. The fatigue tests were conducted under load control, with a stationary sinusoidal waveform and a frequency of 10 Hz.

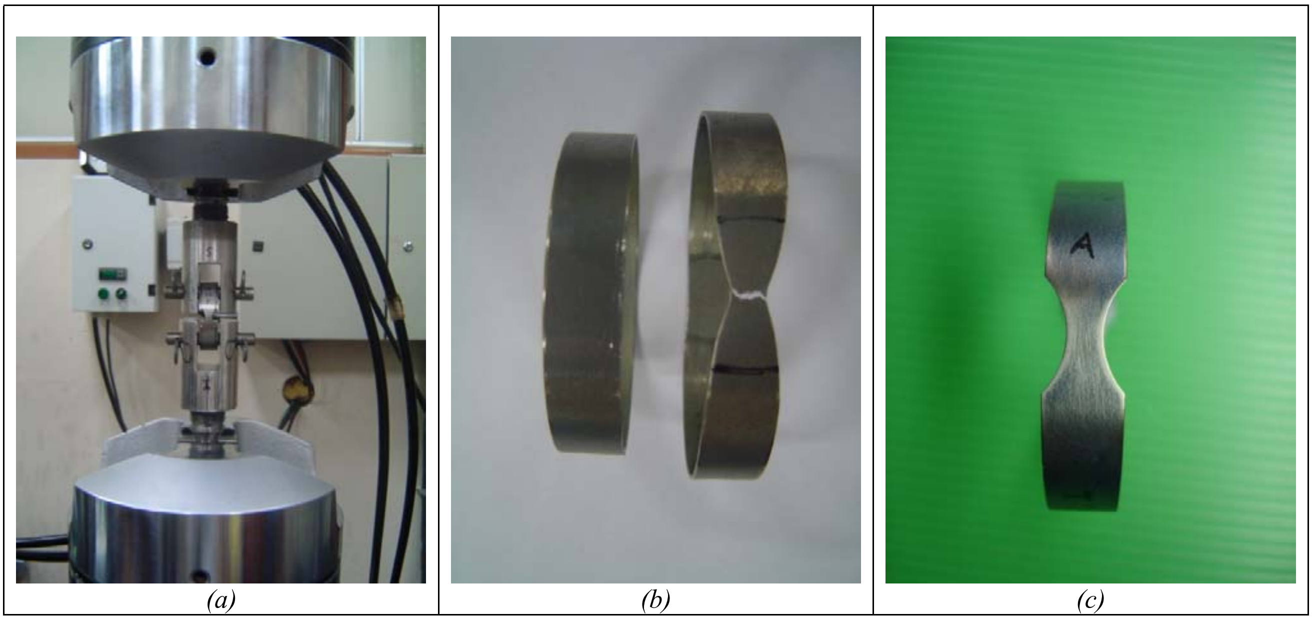

(a) *(b)* *(c)*

Figure 5. Mechanical tests: *(a)* test rig; *(b)* untested and tested tensile specimens; *(c)* fatigue specimen

3. RESULTS AND DISCUSSION

The experimental results and their discussion are presented in the next sections.

3.1. Stress state during pressurization tests

The ring-shaped specimens were cut from the straight sections of the tubular test pieces. During pressurization, these sites were subjected to plane stress conditions, given by the well-known expressions for the hoop and longitudinal stresses in a thin-walled tube. The maximum principal stress σ_1 (hoop direction) is given by Eq. (1), where p is the internal pressure, r the inner radius and t is the wall thickness. The longitudinal stress is half of the maximum stress, while the minimum principal stress (radial direction) is approximately zero. The effective stress for the von Mises (octahedral shear) criterion, usually adopted for multiaxial fatigue, is given by Eq. (2).

$$\sigma_1 = \frac{pr}{t} \tag{1}$$

$$\sigma_{ef} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} = \frac{\sqrt{3}}{2}\sigma_1 \qquad (2)$$

The results for the two maximum pressure levels adopted in this work are given in Tab. 2. These values are lower than the expected yield stress of Ti A40 at the adopted test temperatures, which is of the order of 80 MPa.

Table 2. Stress values for the two maximum pressures adopted in the tests.

Pressure, psi (MPa)	σ_1 , MPa	σ_{ef} , MPa
150 (1.034)	36	31
250 (1.724)	60	52

3.2. Tensile properties

The results of the tensile tests are given in Tab. 3. These results confirm that the mechanical properties of Ti A40 in the SR condition are in accordance to the requisites for commercially pure titanium, classified as ASTM grade 2. The results for TD00 specimens allow concluding that the fabrication process did not alter the tensile properties of the material located in the straight sections of the tubular test pieces. The same can be concluded for the cyclic pressurization tests conducted at 150 psi, except for the ultimate tensile strength, which seems to slightly decrease as the duct is cycled at higher temperatures. As for the duct cycled at 250 psi, a clear increase occurs in the yield stress, accompanied by a decrease in the elongation. In this case, the higher stresses associated to the increased pressure may have caused some cyclic hardening to occur. A more developed difusional process may also have contributed to this result.

Table 3. Tensile properties at room temperature.

Condition / Property	σ_e (MPa)	σ_t (MPa)	ΔL (%)
SR (1)	288 ± 24	430 ± 10	76 ± 6
TD00 (2)	284	409	72
TD150-300 (2)	284	392	79
TD150-400 (2)	274	385	75
TD250-300 (2)	314	434	57

(1) Mean value and standard deviation of five test results
(2) Average of two test results

3.3. Fatigue behavior

The fatigue results are presented in Fig. 6 as Stress-Life curves in which the average number of cycles (five tests for the SR condition; two or three for the remaining conditions) is plotted against the maximum nominal cyclic stress. The observed decrease in the fatigue results of the TD00 specimens in relation to the SR specimens can be attributed to small stress raisers introduced by handling during the fabrication process. Figure 6 shows also that the fatigue resistance of the material decreases even more when it is pressurized in the workbench, being a clear indication that the material suffers fatigue damage accumulation during the high temperature cyclic pressurization tests. The differences between the material conditions clearly decrease as σ_{max} is increased, which is an indication that they are due mainly to small surface stress concentrators that are annihilated as the yield stress is approached. It is also clear from the results that the TD150-300 specimens have higher fatigue resistance when compared to the other cyclic pressurization conditions, which is in accordance to the notion that the less rigorous pressure-temperature combination causes less damage in the material. Moreover, for the presented life range, the fatigue curves of TD150-400 and TD250-300 specimens are virtually the same, indicating similar effects of the adopted pressure and temperature increases, despite the differences found in the tensile properties of these conditions, see Tab. 3.

3.4. Fractographic Analysis

The examination of the tensile specimens fracture surfaces revealed, in all of the material conditions, high concentration of voids caused by the low work-hardening behavior of titanium, allowing more plastic deformation to occur before a stress sufficient to cause fracture was reached, see Fig. 7. The slip systems and the presence of more than one operative twinning system are the main reasons for titanium to exhibit this extensive ductility.

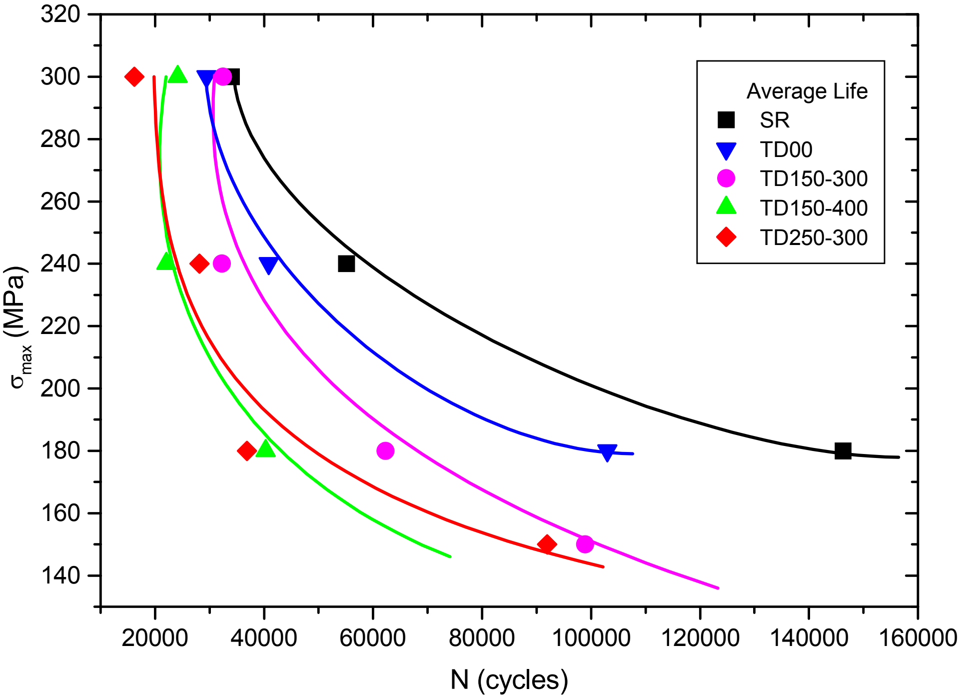


Figure 6. Stress-Life curves for the various tested conditions

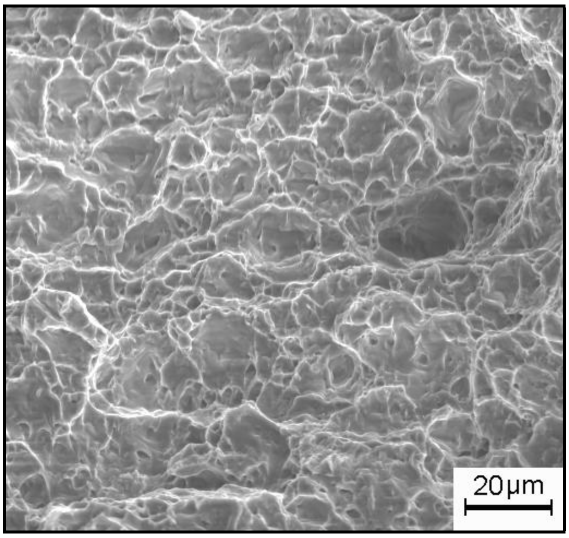
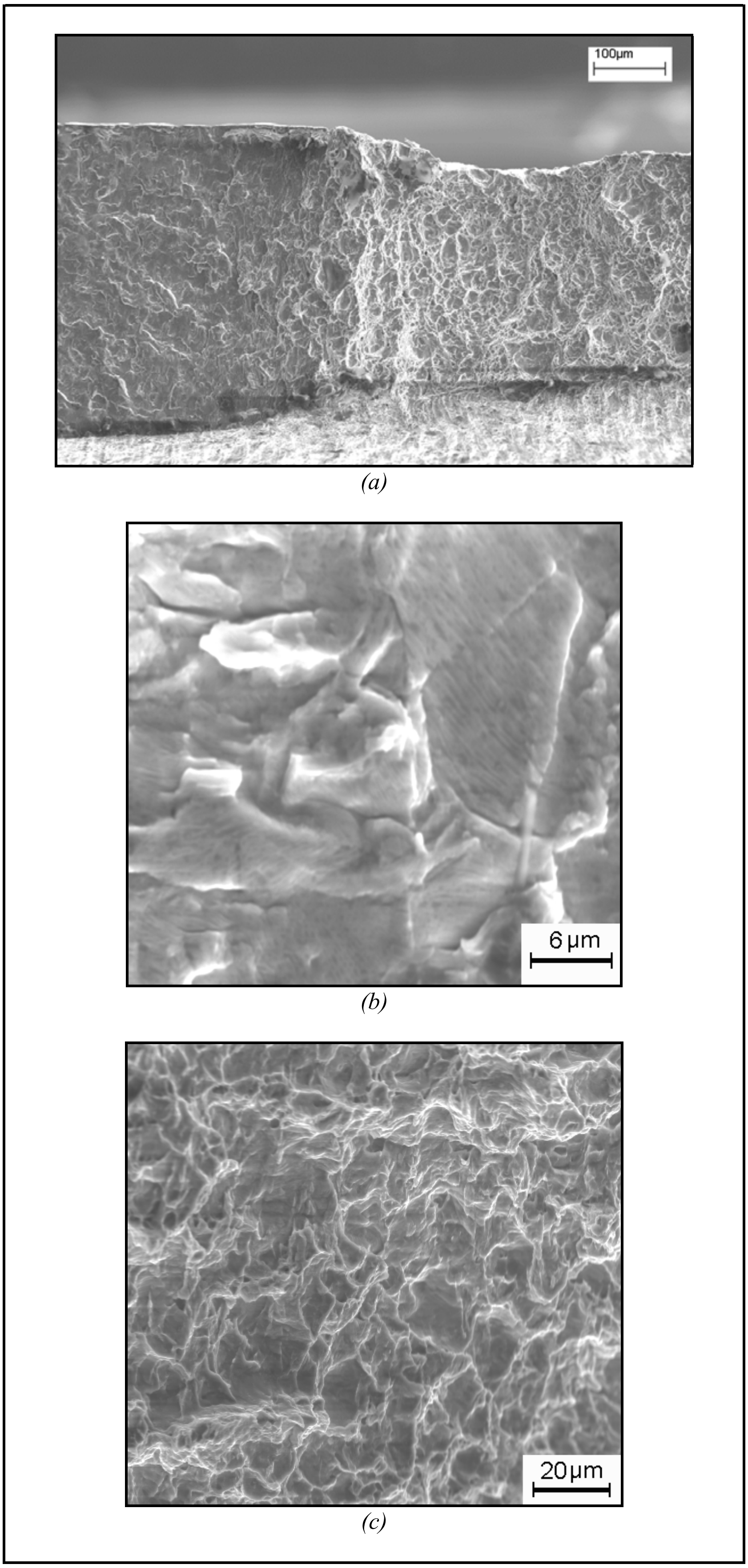


Figure 7. Typical ductile fracture observed in the tensile specimens (TD250-300 condition)

The observed fractured surfaces of the fatigue specimens also presented the same features for the various material conditions. Figure 8 shows these main features. The fracture surfaces usually presented two regions (Fig. 8*a*), corresponding to the stable crack growth and final rupture areas. Multiple crack initiation sites were found in some specimens, leading to non-propagating cracks. The transgranular crack propagation region presents fatigue striations (Fig. 8*b*). The final rupture area shows extensive plastic deformation (Fig. 8*c*). The residual forced fracture is a transgranular dimpled fracture. In spite of the differences in the tensile and fatigue properties, similar fracture appearances were observed in all of the specimens. This is indicative that, if some interstitial absorption occurred during the high temperature pressurization tests, it was not enough to promote changes in the failure mechanisms.



(a)

(b)

(c)

Figure 8. Typical fatigue fracture: *(a)* general view (SR); *(b)* crack propagation (TD00); *(c)* final rupture (TD250-300)

4. CONCLUSION

This work demonstrated that it is feasible to perform laboratory simulations of service conditions of aircraft pneumatic ducts. The presented preliminary results have confirmed that thin-walled titanium ducts suffer fatigue damage accumulation. An investigation is in course, in order to clarify the damage mechanisms by means of microstructure, chemical and surface analyses, and quantify fatigue damage in order to allow life predictions to be done.

5. ACKNOWLEDGEMENTS

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