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Limit load of notched Ti-6Al-4V specimens under axial fatigue

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Abstract

Ti-6Al-4V is used to manufacture aircraft components, that are subjected to fatigue loads during their service life. These components exhibit flaws and are susceptible to impact damage. Therefore, it is important to study the fatigue behaviour of Ti-6Al-4V in the presence of defects to accurately evaluate the fatigue life of components. This paper reports the limit load of notched Ti-6Al-4V specimens not subjected to solution treatment and over-aging under axial fatigue. The tests are carried out in inert environments using a step loading procedure, with a load ratio $R = 0$. The limit loads of the specimens with a notch depth / width of the specimens' gauge section ratio $d / D = 0.0439$ and $d / D = 0.0877$ are similar and higher than the limit load of the specimen with $d / D = 0.1754$ since the net area at the minimum cross section of the third specimen is much smaller than the areas of the other two specimens. The nominal stress at failure referred to the net area is similar for the fatigued specimens.

Keywords: Ti-6Al-4V; fatigue; notches; experiments

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1. Introduction

Fatigue is a common cause of service failure in aircraft components (Findlay, 2002; Solob et al., 2020). The fatigue life of components is influenced by loading and environmental conditions, engineering design, material of construction and manufacturing (Becker et al., 2002; Khosravani et al., 2022; Monkova et al., 2022; Vukelic et al., 2022). Due to local stress concentrations (Božić et al., 2014; Mlikota et al., 2017, 2018, 2021a), fatigue cracks can initiate at defects introduced during manufacturing and service and propagate (Božić et al., 2010a, 2010b, 2011, 2012; Sedmak et al.

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2022; Vučković et al., 2018) causing the premature failure of components (Pastorcic et al., 2019; Vukelić et al., 2020). The residual stresses generated during manufacturing processes of components contribute to alter their fatigue life (Božić et al., 2018; Mlikota et al. 2021b; Baragetti et al., 2019b, 2020; Baragetti and Arcieri, 2022) and the combination of stress concentration and residual stress also leads to fatigue failure of components damaged by the impact of foreign objects (Arcieri et al., 2021, 2022, 2023).

Ti-6Al-4V is one of the most used alloys in aircraft field besides composite materials (Grbović et al., 2022) thanks to its high strength-to-density ratio and outstanding corrosion resistance (Lütjering, 2007). Structural airframe and engine components, which are typically subjected to fatigue loads during their service life, are made of Ti-6Al-4V. These components exhibit defects and are frequently susceptible to impact damage. For this reason, it is important to study the fatigue behaviour of Ti-6Al-4V alloy in the presence of defects, in order to accurately evaluate the fatigue life of each component and avoid unexpected failures (Babić et al. 2018, 2019, 2020; Cazin et al., 2020; Braut et al., 2021a). The analysis must be conducted for different defect geometries since the propagation of small cracks is fast (Gangloff, 1985) and small-sized defects introduce high stresses and steep stress gradients (Morel et al., 2009). The notch fatigue behaviour of Ti-6Al-4V in inert and aggressive environments is described in Baragetti (2013, 2014) and summarized in Baragetti and Arcieri (2018) for the alloy subjected to Solution Treatment and Over-Aging (STOA), which consists of solution treatment and vacuum annealing (Baragetti, 2013). The presence of this treatment increases the component manufacturing cost and for this reason it is important to assess the strength of Ti-6Al-4V in the absence of STOA. The behaviour of Ti-6Al-4V without STOA under quasi-static loading is reported in Baragetti et al. (2018, 2019a) for various notch geometries in inert and aggressive environments while the investigation of the fatigue behaviour is the subject of this paper. For this purpose, axial fatigue tests are conducted on Ti-6Al-4V specimens not subjected to STOA in inert environments with a load ratio R = 0 (Muttoni and Legrenzi, 2022; Arcieri and Baragetti, 2023a, 2023b). Notched specimens are tested and various notch depths are investigated. According to the results, the limit loads of the specimens with low notch depth / width of the specimens' gauge section ratios are similar and higher than the limit load of the specimen with a higher ratio while the nominal stress at failure referred to the net area is similar for the tested specimens.

Nomenclature

d	notch depth
D	width of the specimens' gauge section
f	frequency of the fatigue tests
L^*	load range which gives a fatigue life of N_l loading cycles
L_f	load range applied to the specimen in the failure load block of the step loading procedure
L_p	load range applied in the load block of the step loading procedure prior to the failure load block
N_f	number of cycles at which the failure occurs in a load block of the step loading procedure
N_l	fatigue life
R	load ratio in the fatigue tests
S1	specimen with d = 0.5 mm
S2	specimen with d = 1.0 mm
S3	specimen with d = 2.0 mm
UTS	ultimate tensile strength of the material
YS	yield stress of the material

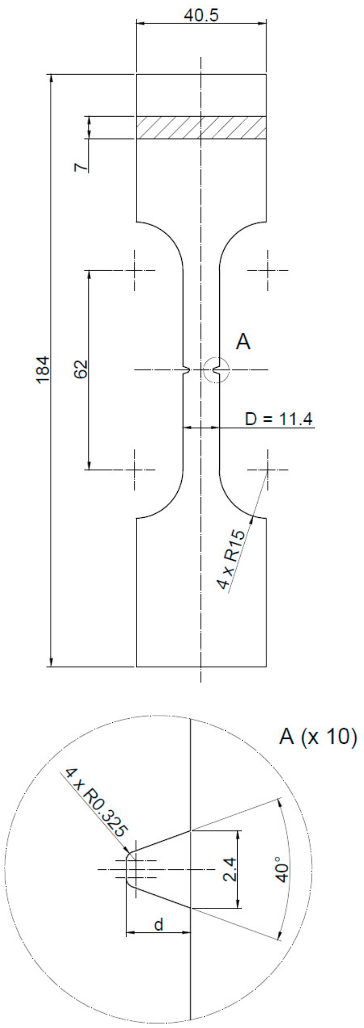
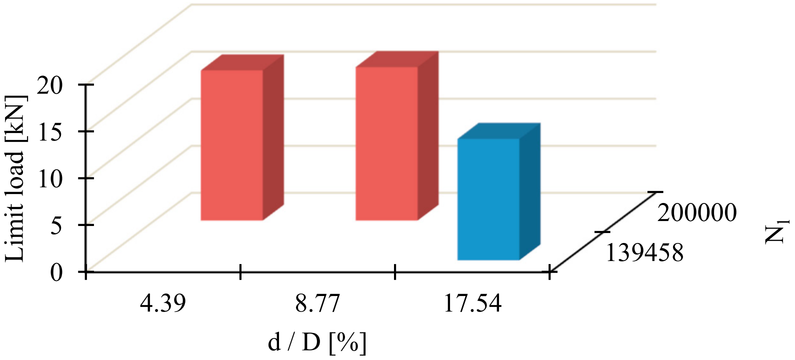


Fig. 1. Geometry of the tested specimens (Arcieri and Baragetti, 2023a, 2023b).

Fig. 2. Testing machine (Terranova et al., 2003).

2. Axial fatigue tests on the Ti-6Al-4V specimens

In order to determine the fatigue limit load of Ti-6Al-4V without STOA in the presence of notches, axial fatigue tests were conducted on specimens with the geometry of Fig. 1 (Arcieri and Baragetti, 2023a, 2023b). The different investigated notch depths, d, are 0.5 mm for specimen S1, 1.0 mm for specimen S2 and 2.0 mm for specimen S3. Being D = 11.4 mm the width of the specimens' gauge section, the following d / D ratios were investigated: 0.0439, 0.0877 and 0.1754. The specimens were fabricated from a Ti-6Al-4V rolled plate whose chemical composition is 5.97 % Al, 4.07 %, 0.20 % Fe, 0.19 % O, 0.003 % C, 0.015 % H, 0.05 % N and Ti bal. (Baragetti and Medolago, 2013). The alloy was not subjected to STOA and its mechanical properties are: ultimate tensile strength UTS = 1000 – 1100 MPa, yield stress YS = 958 – 1050 MPa (Baragetti and Medolago, 2013; Baragetti, 2013). The different notches were made by milling at low cutting speed in order to introduce low residual stresses in the specimens. After the notches were produced, the specimens were not stress relieved.



d / D [%]	L_p [kN]	L_f [kN]	N_f	L* [kN]
4.39	13.9	17.0	135544	16.0
8.77	14.5	16.8	160650	16.3
17.54	-	13.0	139458	-

Fig. 3. Results of the fatigue tests on the notched specimens (Arcieri and Baragetti, 2023a, 2023b).

The surface of the Ti-6Al-4V titanium alloy specimens, as well as that of the notches, was polished with grit paper and finished with diamond paste before performing the axial fatigue tests. The specimens were tested in inert environments. The specimen with two notches of 2 mm depth (S3) was tested in air, while for the specimens with d = 0.5 and 1.0 mm (S1 and S2) vacuum conditions were achieved by placing a layer of insulating tape over the surface of the notches. The fatigue tests were performed with the patented testing machine (Fig. 2) in the Structural Mechanics Laboratory at the University of Bergamo (Terranova et al., 2003) using the step loading procedure provided by Nicholas (2002). According to Nicholas' procedure, various load blocks are sequentially implemented on each specimen. In each load block, the specimen is loaded for N_l under constant amplitude loading, being N_l the number of cycles at which the load to failure is to be determined. If the specimen runs out in the load block, the applied load is incrementally increased in the subsequent ones. Given the number of cycles $N_f \leq N_l$ at which the failure occurs in a load block, the load range L* which gives a fatigue life of N_l loading cycles can be evaluated as a linear interpolation (equation 1) between the load range applied to the specimen in the load block where it fails, L_f, and the load range applied in the previous load block, L_p:

$$L^* = L_p + \frac{N_f}{N_l}(L_f - L_p) \tag{1}$$

Nicholas' procedure provides preliminary results similarly to Locati method (Braut et al., 2021b) and it is suitable when fatigue cracks propagate rapidly to failure. The evaluation of the specimen fatigue strength could be affected by the possible growth of cracks in the load blocks prior to the one in which failure occurs, with consequent alteration of the stress state in the specimen. The ideal situation corresponds to the crack propagation occurring completely in the failure load block (Nicholas, 2002). The experimental tests described in this work were conducted with load blocks of 200000 loading cycles. In each load block the applied load ratio R was 0 and the frequency f was 5 Hz.

The experimental results are summarized in Fig. 3. The failure of the specimen S1 with d / D = 0.0439 occurred after N_f = 135544 cycles under a load range L_p of 17.0 kN, while the specimen S2 with d / D = 0.0877 failed with L_p = 16.8 kN after N_f = 160650 cycles. The failure of the specimen S3 with d / D = 0.1754 occurred in the first load block, after 139458 cycles, with a load range L_p of 13.0 kN and therefore the step loading formula (equation 1) was not adopted. The load capacity of the specimens S1 and S2 is similar (16.0 kN and 16.3 kN for 200000 loading cycles), while that of the specimen S3 is lower (13.0 kN for 139458 loading cycles). This behavior is attributable to the different net areas of the specimens at the minimum cross section, with the net area of S2 equal to 90 % of the net area of S1 and the area of S3 equal to about 70 % of the net area of S1. By calculating the nominal stress at failure referred to the net area, the following values are obtained: 220 MPa for d / D = 0.0439, 248 MPa for d / D = 0.0877 and 251 MPa for d / D = 0.1754. The stress at failure is therefore quite similar for the three tested specimens.

3. Conclusions and future developments

This work reports the limit load of notched Ti-6Al-4V specimens not subjected to STOA under axial fatigue in inert environments. The tests are conducted using a step loading procedure, with a stress ratio R = 0. The load capacity of the specimen with d / D = 0.0439 is similar to that of the specimen with d / D = 0.0877. The limit load of the specimen with d / D = 0.1754 is lower due to a reduced net area at the minimum cross section compared to the areas of the other two specimens. The nominal stress at failure is instead quite similar for the three tested specimens.

The notch fatigue behavior of Ti-6Al-4V in the absence of STOA treatment can be deepened in future studies by conducting further experimental tests. The driving forces involved in the failure mechanism would be identified with the analysis of the fracture surfaces of the tested specimens. Numerical analyses would be performed to predict the behavior of the specimens as done in Arcieri et al. (2018) and Baragetti and Arcieri (2019, 2020) for other mechanical problems.

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