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Experimental testing of Ti-6Al-4V under axial cyclic loading

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Abstract

The Ti-6Al-4V titanium alloy is commonly used in the manufacturing of aircraft components. These components are typically subjected to cyclic stresses during their operational life. The propagation of existing defects contributes to fatigue degradation, making a comprehensive study of the fatigue response of Ti-6Al-4V containing defects crucial for an accurate evaluation of component durability. This paper presents the outcomes of experiments conducted in an inert environment using smooth and notched Ti-6Al-4V specimens subjected to axial cyclic loading. The fatigue strength appears comparable among the notched specimens and is significantly higher for the smooth ones. The failure of one of the tested smooth specimens started from a location different from where stress concentration is expected, probably due to the presence of a micro notch.

Keywords: Ti-6Al-4V; cyclic loading; notches and defects

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1. Introduction

Due to a remarkable corrosion protection capability and a high strength-to-density ratio, the Ti-6Al-4V titanium alloy is commonly used in aircraft engineering to manufacture airframe and engine structural components (Lütjering, 2007), along with 7075-T6 aluminum alloy (Baragetti et al., 2019b; 2020) and high-strength alloyed steel (Solob et al., 2020). Aircraft components are typically subjected to fatigue stresses during their service life and present defects that can result from manufacturing processes (Grandt, 2011; Gupta et al., 2022, 2023; Renzo et al., 2022; Liović et al., 2023) and possible impact of foreign objects (Peters and Ritchie, 2000; Arcieri et al., 2021, 2022, 2023b).

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Consequently, localized stress concentrations (Morel et al., 2009) and residual stresses (Baragetti and Tordini, 2007; Baragetti et al., 2000; Mlikota et al., 2021) associated with the presence of such defects lead to the initiation of fatigue cracks, which propagate until failure (Božić et al., 2010; Mlikota et al., 2017, 2018; Čakmak et al., 2019; Cazin et al., 2020; Vukelić et al., 2020; Khosravani et al., 2022).

With the spread of additive manufacturing, recent studies in the literature focus on the fatigue properties of Ti-6Al-4V components made with this technology (Van Hooreweder et al., 2012; Leuders, 2013; Viespoli et al., 2020; Liović et al., 2021; Konda, 2023; Verma et al., 2023) pointing out that the high porosity and percentage of defects introduced is responsible for a significant decrease in fatigue life.

In light of the above, the examination of the fatigue response of Ti-6Al-4V in the presence of defects is crucial for accurately assessing the behavior and durability of components. This has been undertaken in studies such as Yetim et al. (2010), Arcieri et al. (2018), Babić et al. (2018, 2019, 2020), Baragetti and Arcieri (2019, 2020), Kožar et al. (2020) and Monkova et al. (2020), addressing different mechanical problems. The behavior of Ti-6Al-4V under quasi-static stress conditions was examined in Baragetti et al. (2018, 2019a), where the detrimental effect on structural integrity provided by the combination of sharp notches with aggressive environments was highlighted. This paper presents the results of the experiments conducted in an inert environment on Ti-6Al-4V specimens with different geometries subjected to axial cyclic loading (Arcieri and Baragetti, 2023a, 2023b; Arcieri et al., 2023a). Fatigue strength appears to be similar among the notched specimens, whereas it is much greater for the smooth ones. The failure of one of the tested smooth specimens started from a point other than where stress concentration is expected, probably due to the presence of a micro notch.

Nomenclature

d	notch depth
N_f	number of cycles at which the failure occurs
N_l	fatigue life
SCF	stress concentration factor
σ^*	stress range corresponding to a fatigue life of N_l loading cycles
σ_f	stress range applied to the specimen in the failure load block
σ_p	stress range applied in the load block before the failure load block

2. Materials and methods

The axial cyclic tests were carried out on flat specimens having the shape depicted in Fig. 1 (Arcieri and Baragetti, 2023a, 2023b; Arcieri et al., 2023a). Smooth and notched specimens were fatigued and for the latter the following values of notch depth were investigated: d = 0.5, 1 and 2 mm. The specimens were made from a rolled plate of Ti-6Al-4V alloy with the following chemical composition: 5.97% aluminum, 4.07% vanadium, 0.20% iron, 0.19% oxygen, 0.003% carbon, 0.015% hydrogen, 0.05% nitrogen and balanced titanium (Baragetti and Medolago, 2013). Ti-6Al-4V was not solution treated and over-aged. As a consequence of the chemical composition and the metallurgical process, the yield stress of the alloy ranges from 958 to 1050 MPa and the ultimate tensile strength ranges from 1000 to 1100 MPa (Baragetti and Medolago, 2013; Baragetti, 2013). To mitigate residual stress effects in the specimens, notches were created by low-speed milling. A plane stress linear elastic finite element analysis was performed on the model of a quarter of the specimens using the Abaqus/Standard code (2021) to determine the stress concentration factor (SCF) for each tested specimen. A homogeneous isotropic elastic material model was used for the analyses and the SCF was determined based on axial stresses. In the case of smooth specimen, stress concentrations occur at the fillet base.

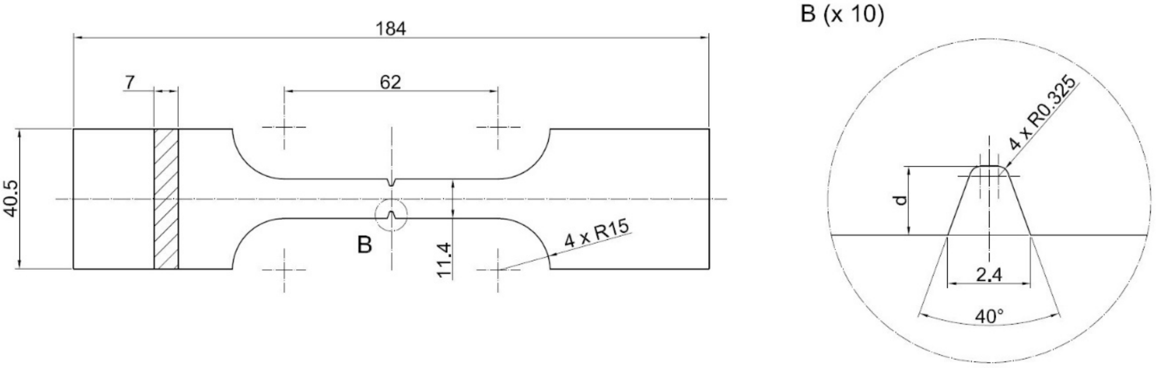

Fig. 1. Shape of the tested specimens, adapted from Arcieri and Baragetti (2023a, 2023b) and Arcieri et al. (2023a).

Before initiating the axial fatigue tests, the surface of the notches and the part of the front and rear surfaces of the specimens near the notches were polished using grit paper and diamond paste. In the case of smooth specimens, the side surfaces were difficult to polish.

The step loading method proposed by Nicholas (2002) was employed for fatigue testing. This approach involves the sequential application of various load blocks to the tested specimens. Each specimen was loaded at constant amplitude for N_l cycles in each load block, where N_l represents the investigated fatigue life and it is equal to 200000 loading cycles in this study. If the specimen does not fail in a load block, an increased stress is applied in the following one. The stress range σ^* at failure corresponding to a fatigue life of N_l loading cycles is calculated using equation 1, where σ_f is the stress range at which the specimen fails, N_f is the number of loading cycles in the failure load block and σ_p is the stress range applied in the prior load block:

$$\sigma^* = \sigma_p + \frac{N_f}{N_l}(\sigma_f - \sigma_p) \tag{1}$$

Nicholas' method provides preliminary fatigue data and fits well when fatigue cracks grow rapidly. However, the potential development of cracks in the load blocks before failure could lead to a modification in the stress state in the specimen, which influences the fatigue behavior.

The fatigue tests were conducted at a frequency of 5 Hz, with a stress ratio equal to 0 and in an inert environment.

3. Results

Fig. 2 illustrates the experimental results, where the data referring to the notched specimens are taken from Arcieri and Baragetti (2023a, 2023b) and Arcieri et al. (2023a). The data that correspond to a number of cycles different from 200000 refer to tests where failure occurred in the first applied load block. In these cases, the step loading formula was not employed. One of the two tested smooth specimens (SCF =1.14) failed in the first load block after 125644 loading cycles, with an applied stress range of 407 MPa. The second smooth specimen failed in the second applied load block after 44633 cycles, under a stress range of 436 MPa. The specimen with a SCF of 2.48 (d = 0.5 mm) failed after 135544 cycles under a stress range of 234 MPa. The specimen with a SCF of 2.91 (d = 1 mm) failed after 160650 cycles at a stress range of 255 MPa. The specimen with a SCF of 3.11 (d = 2 mm) failed in the first load block after 139458 cycles, with a stress range of 251 MPa. Observing Fig. 2, it is evident that the fatigue strength of the smooth specimens significantly exceeds that of all the notched specimens tested while the stress at failure is similar among the notched specimens. Given the shape of the notch, its depth seems to partially influence the fatigue resistance of the specimens. Analyzing the fatigue behavior from a phenomenological perspective, the failure of one of the tested smooth specimens did not start from the fillet base but rather from a point on the side of the specimen's gauge section, where a micro notch probably existed.

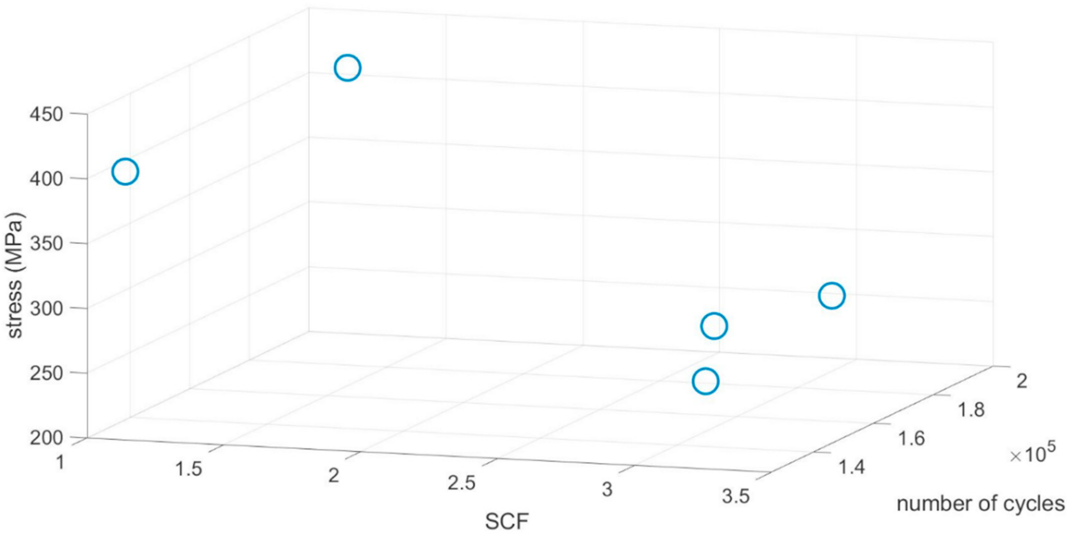

Fig. 2. Experimental results, some data are from Arcieri and Baragetti (2023a, 2023b) and Arcieri et al. (2023a).

4. Conclusions

This study compares the strengths of smooth (SCF = 1.14) and notched (SCF = 2.48, 2.91 and 3.11) Ti-6Al-4V specimens under axial cyclic loading. The tests were carried out in an inert atmosphere with a stress ratio equal to 0 and adopting a step loading method. While the stress at failure is similar among the notched specimens, the fatigue strength of the smooth specimens is significantly higher. This suggests that, given the shape of the notch, its depth probably partially influences the fatigue resistance. One of the tested smooth specimens failed at a point on the side of the specimen's gauge section, likely due to the presence of a micro notch. Future developments could involve an in-depth analysis of the failure mechanism, including an assessment of potential contributions from micro notches that may exist.

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