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High temperature fatigue tests of notched specimens made of titanium Grade 2

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ABSTRACT

The present paper summarizes data from uniaxial-tension load controlled fatigue tests on notched specimens made of titanium Grade 2. The tests are performed at room temperature and 500 °C that, having regard to the properties of titanium Grades 2, can be considered as a limit temperature. Indeed, in the final application, a component can be intentionally or unintentionally pushed to the limit. Commercially Pure (CP) titanium Grade 2 is employed for high-performance applications, such as jet engine and airframe components (e.g. ductwork, brackets), or small rolls for hot-rolling of metals, and it is subjected, in service, to a combination of mechanical and moderate thermal loadings that under uncontrolled conditions can become very important. Two geometries are considered: semicircular notches and plates weakened by symmetric V-notches, with opening angle and tip radius being equal to 90° and 0.75 mm, respectively. The present work is motivated by the fact that, at the best of authors' knowledge, no results seem to be available for notched components tested at high temperature made of titanium Grade 2.

After a brief literature review of the recent works available for titanium in general, the Grade 2 is introduced in the "material" section. Subsequently, the experimental procedure is described in detail and the new fatigue data are summarized in terms of stress range, at the considered temperatures. Finally, the results are re-analyzed by means of the mean value of the Strain Energy Density (SED) and the advantages of the method are pointed out.

1. Introduction

In general, the titanium has been recognized for its strategic importance as a unique lightweight, high strength alloyed, structurally efficient metal for critical, high-performance applications, such as jet engine and airframe components. One of the primary attributes of these alloys, is the elevated strength-to-density ratio which represents the traditional primary incentive for selection and design into aerospace engines and airframe structures and components. Moreover, very low density and the exceptional corrosion resistance make titanium alloys very attractive for high temperature applications such as hot gas turbine and automotive engine components, where more creep-resistant alloys are required for temperatures as high as 600 °C. Titanium is a very well-established heat transfer material that shows a good strength and ability to fully withstand corrosion and erosion at high temperature [1–3].

The literature about titanium and its alloys is very wide and diversified. Different titanium alloys have been largely analyzed in a number of papers, considering different topics and point of views, e.g. fatigue resistance in air and corrosive environment, effects of high temperature, microstructural aspects, notch sensitivity, crack propagation. Among the recent works, in [4], the crack growth behavior in titanium alloys at high temperature was examined. A focus is made on the concept that the fracture mechanisms in these alloys are governed by the slip process taking place within the crack tip region. The effect of different parameters (load frequency, hold time period) on the damaging was also analyzed. In [5], it was investigated the fatigue crack propagation behavior in commercial pure Ti severely deformed by accumulative roll bonding (ARB) process. It was found a different mechanical behavior between specimens and starting sheet, maybe due to crack closure phenomena related to the ARB process. In [6] it was studied the effect of notch geometry on the critical distance for high cycle fatigue predictions of Ti–6Al–4V. The experimental data were used in combination with finite element analyses to determine a 'critical distance' for all of the considered geometries. It was determined from the stress distribution surrounding the notch in combination with fatigue limit stress data from un-notched specimens. However, it was not possible to define a unique synthesis parameter for the fatigue assessment of all of the specimen geometries. In [7] existing multiaxial fatigue models are examined in order to

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determine their suitability for estimating the fatigue damage in Ti–6Al–4V under combined modes. Both equivalent stress-based models and critical plane approaches were discussed but only one equivalent stress model and two critical plane models showed promising results for the range of loadings and material considered. Another newsworthy paper is presented by [8], in which a predictive model for the fatigue crack propagation in metal alloys in laboratory air is proposed. The model was applied to different alloys, such as Ti–6Al–4V with very promising results.

In [9] a study on the fatigue behavior of notch sensitivity of Ti–6Al–4V is presented. Notch sensitivity data was compared with those of steels. The results indicated that the notched material presented a different sensitivity when the specimens were subjected to high cycle fatigue (HCF) or low cycle fatigue (LCF) tests. The notch sensitivity of this alloy was shown generally to be much lower than steels with comparable ultimate strength values. The fatigue behavior of notched Ti–6Al–4V in air and corrosive environment has been investigated in [10]. Axial fatigue tests ($R = 0.1$) in air and recirculated 3.5 wt.% NaCl solution were carried out, considering smooth and V-notched specimens.

Considering the specific Grade 2, an interesting work is presented in [11], in which the effect of thermal exposure on the room temperature tensile properties of Grade 2 titanium was studied. It was showed that at high temperature the ductility of samples exposed in air is dramatically reduced and a protective atmosphere is required during heat treatment.

After this brief literature review it is possible to conclude that different phenomena related to different titanium alloys have been investigated, and some other recent papers that deal with different aspects of titanium and its alloys are available in literature [12–19]. However, when dealing with high temperature fatigue of notch components made of titanium, the number of papers is reduced drastically, and moreover, no papers are available for the specific titanium alloy considered in this work (Grade 2), which among the traditional applications at room temperature, it could be used at moderate high temperatures. With the aim to fill this lack, since the significant industrial relevance of the considered material, this study is carried out to investigate the high temperature fatigue behavior of notched specimens made of titanium Grade 2. Semicircular and V-notched specimens are considered. They have been tested at room temperature and 500 °C in laboratory air. At the best of authors' knowledge, a complete set of data from V-notches and semicircular notches at high temperature made of titanium Grade 2 is not available in literature. The aim of this experimental study is to present a set of new results from high-temperature fatigue tests in the high-cycle regime and to give a useful tool to design against fatigue, considering a temperature which, having regard to the properties of titanium Grades 2, can be considered as a limit temperature. Indeed, it is well known that sometimes, in the final applications, component can be intentionally or unintentionally pushed to the limit.

The tests have been performed under uniaxial tension and load-controlled conditions. At last, a final synthesis of the results is carried out by means of the strain energy density approach, as recently made by the present authors for Cu–Be alloys and 40CrMoV13.9 [20–22] in order to propose an easy and fast tool to design against fatigue, regardless of the specimen geometries.

2. Material properties and experimental procedures

2.1. Titanium Grade 2 and specimen geometries

Different titanium grades are available for industrial application, among them the first four are the commercially pure classified. In order to keep production costs as low as possible, "Commercially Pure" (CP) titanium has acceptable mechanical properties and has been used for numerous applications. The titanium under investigation in the present paper is an unalloyed Grade 2, which is called the "workhorse" of the CP titanium industry, thanks to its varied usability and wide availability. It shares many of the same qualities as Grade 1 titanium, but it is slightly stronger, while both are equally corrosion resistant. Grade 2 possesses good weldability, strength, ductility and formability. This makes Grade 2 titanium bars and sheet are the prime choice for many fields of applications. In general, CP Titanium Grade 2 may be considered in any application where formability and corrosion resistance are important, and strength requirements are moderate. Some examples of aerospace applications have included airframe skins in "warm" areas, ductwork, brackets, galley equipment and pipes, where also high temperature needs to be handled. The Grade 2 Ti has also been widely used in marine and chemical applications such as condensers, evaporators, reaction vessels for chemical processing, tubing and tube headers in desalinization plants. Other uses have included items such as jigs, baskets, cathodes and starter-sheet blanks for the electroplating industry. It is well known that sometimes, in the final applications, component can be intentionally or unintentionally pushed to the limit (e.g. hot-rolling of metal), for this reason it is very interesting to study the behavior of this material at a temperature moderately higher than the common use.

Regarding the specimens under investigation in the present paper, they are provided in annealed condition. The mechanical properties obtained through tensile tests, at room and 500 °C, are reported in Table 1: the Young modulus is affected by a moderate variation, being at room temperature equal to 103 GPa and at high temperature equal to 75 GPa, that corresponds to a reduction of 27%. Substantial differences, instead, are registered for the tensile properties: σ_Y decreases from 350 MPa (room temp.) to 175 MPa (500 °C), σ_R from 544 MPa (room temp.) to 227 MPa (500 °C) as might be expected.

As stated previously, Grade 2 is considered CP titanium but for the sake of completeness a chemical analysis has been carried out on the specimens under investigation. The results are given in Table 2 and show a percentage of titanium of 99.78%, while all the impurities have a percentage that is below the acceptable maximum limit for Grade 2.

Two specimen geometries were considered:

- Plates weakened by lateral symmetric V-notches, with a net cross section of 30 mm × 3 mm and a total length of 350 mm (see Fig. 1). The notches were characterized by a depth, a, equal to 10 mm, an opening angle, 2α, equal to 90° and a notch tip radius $\rho = 0.75$ mm. This geometry results in a theoretical stress concentration factor $K_{t,n} = 5.38$ (on the net area).
- Plates weakened by lateral symmetric semicircular notches, with a net cross section of 30 mm × 3 mm. The notches were characterized by a radius $\rho = 10$ mm. The stress concentration factor, $K_{t,n}$ (on the net area), is 1.86. The geometry is shown in detail in Fig. 2.

The specimens were designed to avoid an increase of temperature near the grippers of the test instrument, for this reason the total length of the specimens is equal to 350 mm, which is higher than the length usually adopted at room temperature.

Table 1
Mechanical properties of the CP titanium Grade 2 under investigation.

	σ_y (0.2%) (MPa)	σ_R (MPa)	E (GPa)
Room temp.	350	544	103
500 °C	175	227	75