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The analysis of cyclic properties of Ti-6Al-4V titanium alloy at room and liquid nitrogen temperature

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ABSTRACT

This paper presents the analysis of Ti-6Al-4V titanium alloy test results. Fatigue tests were carried out at room temperature and at the temperature of liquid nitrogen using single sample method. The values of plastic strain, cyclic modulus, cyclic yield stress and fatigue fracture surface were analyzed. The results of the tests were compared to the results from the monotonic tensile test. The presented analysis allowed to determine the value of the total strain at which there is a significant change in the material properties of the tested alloy. Two intervals are distinguished on the basis of this value, which are characterized by the range of low strain and the range of high strain. Different material properties were used in these intervals for analytical description of the cyclic material properties. The analytical description was based on the modification of the Ramberg-Osgood model.

1. Introduction

Due to the relatively high rigidity and strength and low density, 80% of the world production of titanium alloys is used in the aerospace industry [1]. Titanium alloys are used in both jet engines and airframes. [1]. Elements of this type of structures are exposed to different temperatures: high, low as well as those close to room temperatures. An example of an element exposed to low temperatures (from −180° to −250°C) is the impeller of H2-turbo-pomp in launch vehicles Ariane 5. This part is made of Ti-6Al-4V alloy. [2].

Structural elements used in the aforementioned structures are provided with various geometric notches, which cause concentration of stress/strain. In such cases, the local strain/stress approach is, among others, used to assess fatigue life [3–5]. In this approach, different types of constitutive equations describing cyclic material properties are used to assess the strain/stress value at the bottom of a notch [6,7]. However, in engineering applications, the most popular description of the cyclic stress-strain curve (CSS) is the Ramberg-Osgood (R-O) model [8,9], which includes the elastic and the plastic component.

The elastic component is described by the modulus of elasticity E, whose correct determination is very important. The modulus of elasticity defines not only elastic strain, but, as a consequence, affects the value of plastic strain as well as the value of the offset cyclic yield stress. In general, moduli determined from the monotonic tensile test (Young's Modulus, Tangent Modulus, and Chord Modulus [10]) and fatigue tests (cyclic moduli) are distinguished.

There is, among others, a cyclic modulus specified for the branches of the rising (reloading) loop and for the branches of the falling (unloading) loop. In the paper [11] it was demonstrated that for Ni-Ti alloy, for research performed at room temperature the cyclic modulus decreases with the first load cycles and then it stabilizes after the 20th load cycle. While in the paper [12] the Ti-Nb alloy was tested at cyclic loading–unloading experiments in compression. Additionally, there is also one more cyclic modulus presented there determined as the slope of a straight line connecting the loop corners. The value of this modulus was between the modulus values determined from the rising and the falling branches. However, for this material, cyclic moduli determined for rising and falling hysteresis loops differed even by up to 35%.

Thus, doubts arise as to which type of modulus should be used to describe CSS. The existing recommendations [13] indicate that the modulus can be estimated by cycling within the elastic limit of the first quarter of the hysteresis loop at the test temperature for each test. The modulus for describing cyclic properties can also be determined as an average value from the value of cyclic moduli determined from the rising and falling branches of the hysteresis loop [14].

A cyclic elastic limit S_{YC} can be determined once the value of the cyclic modulus is determined. In the absence of an explicit yield stress, it is determined as some offset of plastic strain. The value of S_{YC} shall differ depending on the offset and the test temperature adopted [15]. In the case of materials that are subject to cyclic softening or hardening,

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that value will also change depending on the loading history. In the paper [16] when testing the Ti-6Al-4V-B alloy at room temperature and under variable load conditions, the S_{YC} value was used to determine the degree of softening caused by cyclic loading. One S_{YC} value was determined without taking into account the changes of that value under the impact of cyclic loads. It has been demonstrated that the tested alloy, compared to yield stress obtained from the monotonic tensile test, is subject to cyclic softening.

The CSS parameters describing the range of plastic strain are most often determined using standard procedures [17,18]. According to these recommendations, the tests should be carried out at least at 5 levels of the control strain value. 3 samples should be tested at each level at the same, constant value of strain amplitude. The stress value at the half life stage of each test is then plotted against the corresponding plastic strain amplitude for determination of CSS parameters. However, this method is expensive and labor-consuming. So alternative methods have been developed which are based on single samples [19,20] with different load programs: incremental step, multiple step – increasing strain and multiple step – decreasing strain. It has been proven [21] that the CSS parameters determined from the incremental test are the most suitable for determining the status of strain in randomly loaded structures. For low-carbon steel [22] the single-sample method based on the incremental step allowed to obtain CSS parameters similar to the parameters obtained from the standard test.

The paper [23] presents the results of tests of the alloy in question at room temperature. The tests were carried out using the standard method with several samples loaded with a constant value of strain amplitude. For the test results obtained, three periods were distinguished at each amplitude level: rapid initial softening, taking only 10–15% of the total lifetime, followed by progressive softening, up to 75–80% of fatigue life and then very rapid descending. In addition, above the total strain value of 1.2%, a temporary period (first few cycles) of material hardening is initially observed, followed by a period of rapid initial softening. The paper presents changes in the material behavior under the influence of variable loads, however, no material data was developed and presented that could be used for engineering applications. A similar situation is in case of the paper [2]. Parameters for description of the R-O model are given in the paper [24] only. The presented parameters concern tests at room temperature only.

In the case of tests at low temperatures, it has been proven that the cryogenic temperature improves and stabilizes the structure of the crystal lattice of alloy metals, which results in their hardening [25]. It has also been proven [26], that long-term exposure of the material to cryogenic temperatures usually leads to the reduction of the size of grains and release the internal stresses. The effect of cryogenic temperature on the behavior of the Ti-6Al-4V alloy during the monotonic tensile test is presented in the paper [27]. The test results show that the yield stress and the ultimate tensile strength increase with decreasing temperature. This material behaved similarly under cyclic loads [2]. The increase in strength at cryogenic temperatures is explained by the fact that the friction stress for moving dislocations increases, the antiphase boundary energy of the precipitates increases and cutting of precipitates by dislocation becomes more difficult [28]. In the above-mentioned studies concerning tests at cryogenic temperatures, the analytical description of the CSS curve was not provided.

The presented analysis of the literature demonstrated that the tested material is periodically hardened and periodically soften. Such behavior the material occurs particularly at room temperatures as well as at elevated temperatures [29]. However, there is no analytical description of cyclic material properties for the Ti-6Al-4V alloy, especially for tests at cryogenic temperature. Until now, no analysis of changes of cyclic moduli and cyclic yield stress under the influence of time-varying loads has been done.

The material's microstructure plays a decisive role in the propagation of fatigue cracks, significantly affects the development and direction of the fracture propagation, and also has a significant impact on the speed of fatigue crack development. The Ti-6Al-4V alloy is a typical two-phase alloy whose microstructure consists of a solid solution α with a A3 network and a solid solution β with a A2 network. Aluminum dissolves in the α phase, stabilizes it and strengthens it heavily, while vanadium stabilizes the β phase. The β phase has a greater plasticity than the α phase. Slip systems for the β phase crystallizing in a regular system with a spatially centered network are $\{110\}\{11\bar{2}\}$ and $\{123\}\langle 11\bar{1}\rangle$, while for the α phase crystallizing in a hexagonal system, the basic slip systems are $\{1\bar{1}00\}\ \langle 11\bar{2}0\rangle$ and $\{1\bar{1}01\}\ \langle 11\bar{2}0\rangle$. In addition to the slip strain mechanism, titanium α (solid solution) can also be subject to strain by twinning, and the number of possible twinning planes is significantly higher than in most other hexagonal structure metals [30,31].

This paper presents studies on the Ti-6Al-4V alloy at room temperature and at the temperature of liquid nitrogen. The tests were carried out under variable load conditions at strain controlled for the cycle asymmetry of R = -1. Cyclic properties for CSS description were determined using the single -sample method by means of a loading program based on an incremental step type program. An analysis was performed for cyclic moduli determined for rising and falling branches of the hysteresis loop. The change in the cyclic yield strength was also analyzed. In addition surface and fatigue fractures of the samples were studied.

2. Object and research program

The material tested in this study is titanium alloy Ti-6Al-4V whose structure is shown in Fig. 1. Chemical composition of this alloy and properties obtained from the static tensile test are presented in Table 1.

The fatigue tests were carried out for specimens taken from a 10 mm thick sheet metal plate. Specimens were cut using Wire Electrical Discharge Machining (WEDM) method and then polished. Dimensions of specimens are shown in the Fig. 2.

The low-cycle tests were performed at room temperature (RT) and immersed in liquid nitrogen (LN). Tests in liquid nitrogen were carried out using a local liquid nitrogen cryogenic chamber. The locality of the liquid nitrogen cryogenic chamber consisted in the fact that the liquid nitrogen in it covered at least the measuring part of the specimen. Photographs taken during RT and LN tests are presented in Fig. 3a and b respectively

Low-cycle tests were performed using the INSTRON 8502 testing machine while controlling the strain value. The tests were carried out using an extensometer with a 10 mm measuring base and a measuring range of ± 1 mm. The tests were carried out at a frequency of 0.2 Hz and a cycle asymmetry ratio of R = -1.

The cyclic material properties were determined by means of a single-sample method. Individual samples were loaded by controlling the strain according to the program shown in Fig. 3a for tests at RT and

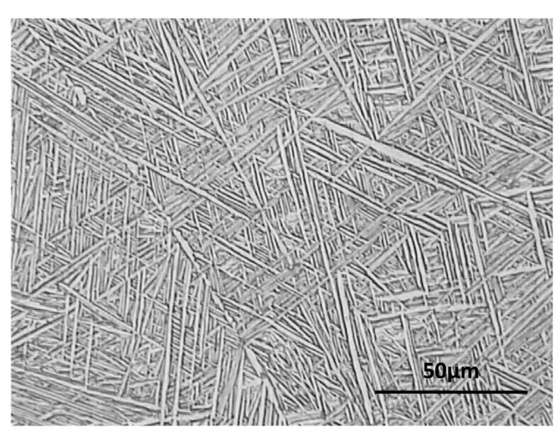

Fig. 1. The structure of Ti-6Al-4V alloy.