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SHORT RESEARCH COMMUNICATION

EVOLUTION OF TENSILE PROPERTIES OF THE TIAL6V4 ALLOY DUE TO THE PRIOR CYCLIC LOADING HISTORY

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The influence of the initial fatigue loading on tensile characteristics of the TiAl6V4 titanium alloy is presented in this work. For cumulative fatigue damage equal to 0.75, a decrease in the pre-fatigue amplitude leads to a lowering in the elongation. Moreover, independent of the amplitude, the loading induces an increase in the yield stress by approximately 100 MPa. An increase in the number of pre-fatigue cycles at a constant amplitude results in a decrease in the elongation. Such mechanical behaviour is related to the cyclic hardening effect and the development of fatigue damage, which clearly affects the tensile characteristics of the alloy.

Keywords: fatigue, metals and alloys, deformation and fracture, cumulative fatigue damage

1. Introduction

Lightweight alloys, including the TiAl6V4 titanium alloy, are commonly used in aerospace, automotive, biomedical, military and civil engineering applications. Some of those structures, may be exposed to extreme loadings due to variety of rapid phenomena, i.e. earthquake, collision, explosion, and impact with a projectile or another object. Many of these undesired actions are taken into account during the process of designing the structure, and the further resistance of the real construction is tested according to the existing standards, e.g. bird impacts on an airplane. However, both the design and test stages are performed by taking into account material properties and constitutive relations assuming the as-received state of the materials (Moćko *et al.*, 2012). When in use, real structures are usually subjected to fatigue loadings as a consequence of the accumulation of fatigue damage is presented. Therefore, the mechanical behaviour of the structure under conditions of extreme loading may be different from those anticipated in the design stage which incorporated properties determined for the as-received material. Although the number of reports concerning this topic is very limited (Sánchez-Santana *et al.*, 2008; Froustey and Lataillade, 2009; Itabashi and Koseki, 2013), on the basis of their results, it may be stated that in the case of some materials, the final mechanical characteristics of a material may be changed substantially when subjected to initial fatigue loading.

Within the framework presented in this article, instead of the common fatigue life analysis, an investigation of the influence of pre-fatigue on the stress-strain curve of the TiAl6V4 titanium alloy has been performed. The tests were conducted at four values of the cyclic stress amplitude and for various numbers of pre-fatigue cycles. The mechanical analyses were supported by SEM micrographs of the fracture surface to determine the change of the fracture mode from ductile to brittle.

2. Experimental method

Hour-glass specimens applied during the tests were machined from an extruded rod made of the TiAl6V4 titanium alloy and subsequently polished to obtain a roughness equal to 0.3, similar to those used in previous works by Socha (2003). Therefore, it was possible to identify the

Table 1. Fatigue loading conditions and selected parameters from standard tensile tests.

Specimen notation	Stress amplitude [MPa]	Average number of cycles	Standard deviation	CFD	Character of fracture	Yield stress [MPa]	Elongation
A	–	–	–	0	ductile	930	0.74
B	957	77	4.5	1	ductile	–	–
C	957	57	–	0.75	ductile	1000	0.61
D	857	3290	281	1	brittle	–	–
E	857	2467	–	0.75	ductile	990	0.45
F	757	10687	1399	1	brittle	–	–
G	757	8015	–	0.75	brittle	985	0.21
H	557	79680	11871	1	brittle	–	–
I	557	59760	–	0.75	brittle	990	0.04
J	557	39840	–	0.50	ductile	997	0.43
K	557	19920	–	0.25	ductile	1050	0.73

location of fatigue damage, and subsequently, to determine true stress and strain values exactly in the location of fatigue damage accumulation. The diameters of the specimen grip and its neck were equal to 8 mm and 4 mm, respectively. The radius of the hour-glass was equal to 20 mm. A transversal extensometer was used to measure the transversal component of the strain. Subsequently, the transversal strain and stress were recalculated into true values of axial strain and stress using the methodology applied in other paper (Socha, 2003). Stress controlled fatigue, pre-fatigue and displacement controlled tensile tests were performed by using an Instron servo-hydraulic testing machine at room temperature. The fully reversible fatigue tests were carried out at a frequency of 1 Hz and stress ratio $R = -1$. The strain rate of the tensile tests was equal to 0.00 1/s. The experimental programme was divided into following stages: (1) determination of Wöhler's curve and the number of cycles required to obtain the assumed level of the cumulative fatigue damage, (2) pre-fatigue test of the specimens, (3) tensile test, and (4) analysis of the fracture surface. The average results obtained from three tests conducted in the same loading conditions are presented in Table 1. Additionally, for the fatigue tests, the standard deviation for the number of cycles was determined.

3. Results

The fatigue loading induces a microstructural evolution divided into three phases (Socha, 2003): (1) elastic deformation of the material without damage; (2) the stage of initiation and stable growth of micro cracks; and (3) coalescence of the dominant crack leading to the total fracture. The cumulative fatigue damage may be described using many more or less complicated equations (Fatemi and Yang, 1998); however, for the purposes of this analysis, the linear method proposed by Miner was used (Miner, 1945).

According to the linear rule of fatigue growth, the CFD parameter presented in Table 1 corresponds to the number of applied cycles related to the fatigue life at a given cyclic amplitude, i.e., CFD = 0 for the as-received material; CFD = 1 for the specimen fractured due to fatigue loadings. An evolution of the microstructure due to fatigue loadings may significantly change the mechanical properties of the material, as determined macroscopically. For the AISI 12L14 and 1215 steels after the pre-fatigue tests, a decrease in the ultimate tensile strength was observed (Itabashi and Koseki, 2013). The decrease in strength was equal to 150 MPa and 50 MPa for the dynamic (Moćko and Kowalewski, 2011) and static loading conditions, respectively. Similar behaviour was observed for the 4140T steel, i.e. introduction of an increasing number of prior cycles induced material softening. The most significant decrease in strength, equal to 300 MPa, was achieved for CFD = 0.75 (Sánchez-Santana *et al.*, 2008). The deterioration effect on the mechanical properties of the material due to fatigue may sometimes be related to the hardening of the material observed at the initial phase of fatigue loading. This type of complex behaviour was determined for the 2017-T3 aluminium alloy (Froustey and Lataillade, 2009). In the case of some materials, i.e. 5454-O (Froustey and Lataillade, 2009) or 6061-T6 (Sánchez-Santana *et al.*, 2008) aluminium alloys, the influence of pre-fatigue on the residual tensile characteristics may be neglected.

The results of the tests are presented in Table 1 and Fig. 1. The fatigue lifetimes of the specimens tested were within the range from 77 to 39840 for the cyclic stress amplitude from 557 MPa to 957 MPa. Figure 1 shows the tensile curves for the TiAl6V4 titanium alloy in the as-received state and for the material after the pre-fatigue tests that correspond to CFD = 0.75. In all cases, the yield stress was observed to increase by approximately 100 MPa due to prior cyclic loading (Paul *et al.*, 2010). For the pre-fatigue tests performed at amplitudes equal to 757 MPa and 857 MPa, for the final stage of plastic deformation, the work hardening effect observed in the materials in the as-received state was found to disappear due to generation of micro-cracks in the material during fatigue (Socha, 2003). The effect of the decrease in strain hardening was very limited for the material after pre-fatigue treatment at a cycle amplitude of 957 MPa. Prior fatigue deformation significantly affects the fracture strain, i.e. a decrease in the cyclic amplitude led to a reduction of the strain at fracture.

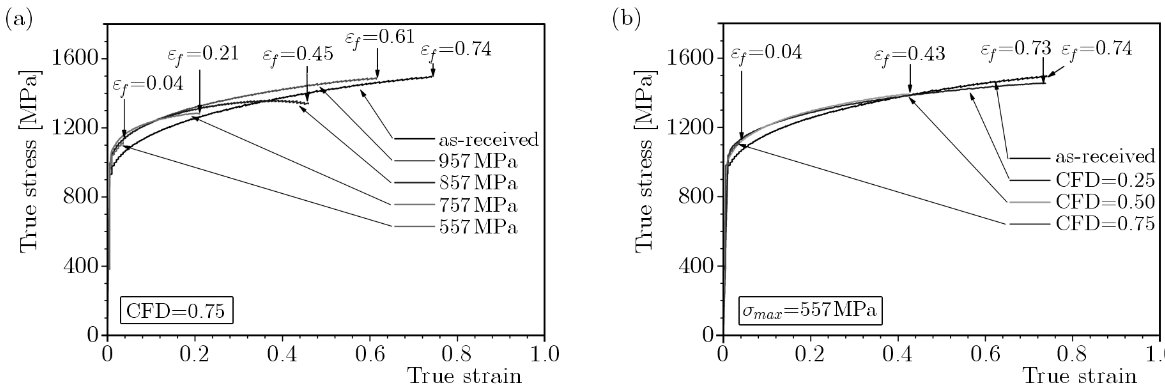

Fig. 1. Stress-strain curves of the TiAl6V4 alloy after pre-fatigue tests at various stress amplitudes for CFD = 0.75 (a) and at stress amplitude equal to 757 MPa for various CFD (b)

The influence of the number of cycles used for prior deformation due to fatigue on the tensile characteristics of the TiAl6V4 is shown in Fig. 1b. A pre-fatigue test corresponding to CFD = 0.25 leads to a slight increase in the yield point equal to approximately 50 MPa and a decrease in the hardening effect in comparison to those determined for the material in the as-received state. An increase in the prior cycles up to CFD = 0.50 reduces the strain at fracture. A further increase in the CFD up to 0.75 results in an even greater decrease in the strain at fracture. As it is easily observed, the number of pre-fatigue cycles has no influence on the shape of the tensile curve, as it only affects the level of strain at fracture.

The evolution of the microstructure due to fatigue loading induces a change of the fracture mechanism type from ductile, as observed for the material in the as-received state (Fig. 2A), to brittle due to the coalescence of micro-cracks (Socha, 2003) (Figs. 2D,F,H). At higher fatigue stress amplitudes, ductile-type fracture may be observed similar to that for the tensile tests of the material in the as-received state (Fig. 2B). In some cases during the tensile tests of the pre-fatigued material, the change of the fracture mode from ductile to brittle may be observed (Sánchez-Santana *et al.*, 2008). For the TiAl6V4 titanium alloy, brittle fracture at CFD = 0.75 was observed for the material after pre-fatigue tests at amplitudes equal to 557 MPa and 757 MPa (Figs. 2G,I), whereas for the higher amplitudes, the fracture surface remained ductile (Figs. 2C,E). The assessment of the fatigue damage, its measurement on the basis of the inelastic strain and the influence on the tensile stress-strain characteristic of AISI 1045 steel were widely discussed in previous works (Socha, 2004; Moćko, 2014; Moćko and Kowalewski, 2011).

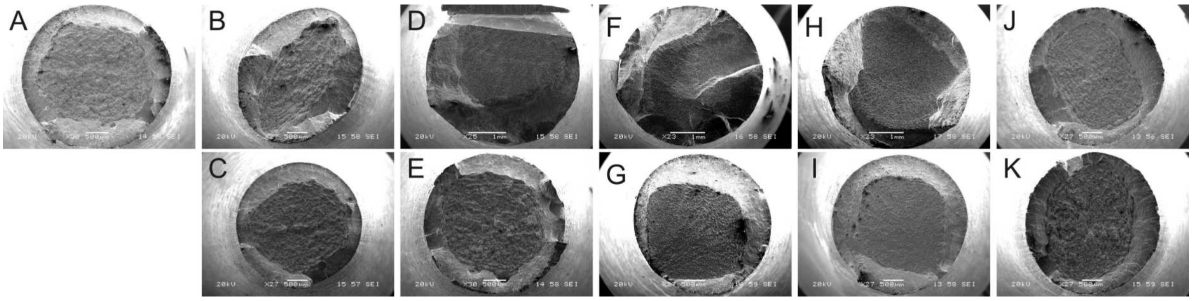

Fig. 2. Optical micrographs of the fracture surface

The development of fatigue damage may be illustrated by an example of tensile tests of the material after pre-fatigue testing at the amplitude of 557 MPa. Initially, at CFD = 0.25, the fracture surface has a ductile character (Fig. 2K); moreover, the fracture strain equal to 0.74 is not strongly affected (Fig. 1b). The increase in the pre-fatigue cycle number to CFD = 0.50 induces a decrease in the elongation to 0.43 and ovalisation of the fracture surface (Fig. 2J), which may be an evidence of fatigue damage growth (Froustey and Lataillade, 2009). A further increase in the CFD to 0.75 results in a clearly observed decrease in the fracture strain to 0.04 followed by a change of the fracture mode to brittle (Fig. 2I).

4. Conclusions

- A decrease in the pre-fatigue amplitude at CFD = 0.75 induces a clearly observed decrease in the fracture strain. Moreover, at amplitudes equal to 757 MPa and 557 MPa, a change from the ductile to the brittle fracture mode was found.
- The initial fatigue loading results in an increase in the yield stress observed for the initial cycles.
- Because fatigue damage growth is a non-linear phenomenon, a clearly observed effect of pre-fatigue at the amplitude of 557 MPa on the tensile curve is present for CFD equal to at least 0.50. The initial cyclic loadings induce the brittle fracture mode together with a decrease in the elongation.

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