ACOUSTIC EMISSION DURING FATIGUE DAMAGE OF NANOSTRUCTURED TITANIUM

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Abstract

Paper present the results of studies on the kinetics of fatigue damage accumulation in structure commercially commercial titanium VT1-0 by acoustic emission (AE) method. Fatigue tests were carried out by bending VT1-0 titanium samples in different structural states. Submicrocrystalline (SMC) grain size structure of 200-300 nm and ultrafinegrained (UFG) grain size structure of 1-2 microns were obtained by equal-channel angular pressing coarse grain (CG) titanium.

The fatigue stages were allocated on the graphs of cumulative AE count after separation of the AE signals by types of AE sources (dislocations, micro- and macro-cracks). It has been established that the late registration of AE signals during testing SMC titanium associated with reduced of the AE signals energy.

Keywords: acoustic emission (AE), identification, equal channel angular pressing, dislocations, microcracks, macrocracks, fatigue, titanium, stages, deformation

1. Introduction

Many products and engineering constructions are used under cyclic loading. The durability of the materials determined by their structure and ability to withstand cyclic loading. Advanced materials should have higher requirements on the mechanical properties. The titanium alloys are very widely used in the aircraft industry, the commercial titanium VT1-0 is used for the manufacture of implants due to unique properties of the titanium [1]. Lately is paid considerable attention to the development of criteria for structural strength, based on the study of the phenomena that underlie the deformation and destruction processes of the nanostructured materials [2]. A common method for producing nanostructured metallic materials is equal channel angular pressing (ECAP) [3].

The materials received by the ECAP method possess unique properties, first of all high hardness and tensile strong. Staging of development of fatigue damages of polycrystalline materials is rather well studied and was considered in many publications [4]. However few experimental works devoted to studying of structural degradation and destruction of the nanostructured materials at fatigue damages propagation.

Most effective to carry out the analysis of mechanisms of damages accumulation according to the parameters of the acoustic emission (AE) recorded during the samples fatigue failure. Mechanisms of development cracks on the basis of separation of AE signals according to types of sources were research earlier. Types of sources correspond to different types of deformation and destruction [5]. Staging of AE at static and cyclic deformation of titanium and other alloys was investigated in works [6, 7] earlier.

The paper presents the results of research using AE method of the kinetics of fatigue damage accumulation to the commercial titanium VT1-0 which is in three structural states: coarse grain, ultrafinegrain and submicrocrystalline.
2. Materials and methods of investigation

The titanium VT1-0 samples were prepared with the ECAP method by a multifold molding with change of a strain axis in combination with the subsequent rolling. At the same time the submicrocrystalline (SMC) structure with grain size of 200-300 nanometers was received. For receiving structure with a particular grain size thermal annealing in the range of temperatures lower than temperature of recrystallization was carried out. Thus, on a number of samples the ultrafinegrained (UFG) structure with the size of grain of 1-2 micrometers and coarse grain (CG) of 20-30 micrometers was received [2].

Samples on the "double blade" type with a radial form of a working zone edges were made of the processed bars. Before fatigue test the surface of samples was ground for elimination of tension concentrators. The sample loading was carried out by exaltation of an alternating electromagnetic field and maintaining of resonance flexural fluctuations of a sample. The rod with a variable weight is rigidly attached to the counter end of a sample. Frequency of resonance fluctuations can make 40-50 Hz depending on value of an elastic modulus of the tested material. The software allows to record change of an oscillation frequency in the course of the fatigue crack birth and propagation. The AE sensor was installed immediately on the fixed part of the sample. The analysis of nature of accumulation of damages was made by a cumulative assessment of change the flexural fluctuations frequency and the AE parameters at cyclic test with the established amplitude of a flexural stress. For a possibility of comparison of the data obtained at the samples test with a various structure all samples were tested at the 500 MPa stress amplitude.

3. Research results and discussion

Schedules of the dependence of an oscillation frequency on number of cycles before destruction for VT1-0 in three various structural states (SMC, UFG and CG) are submitted in fig. 1.

![Figure 1. Schedules of the dependence of an oscillation frequency for the samples: a) SMC, b) UFG and c) CG](image-url)
Frequency of resonance oscillations for the majority of samples with various structure, decreases according to the law close to parabolic and nature of its change significantly does not differ. Significantly different durability samples are tested at the same stress amplitude of 500 MPa. CG structural samples failure at achievement of 25-35 thousand cycles, in UFG structural samples – at 75-85 thousand cycles, and exemplars with SMC structure failure at 100-120 thousand cycles. Decreasing grain size leads to significant improvement of durability. Fracture or period of the durability of the sample accepted the number of cycles until the moment of reducing the frequency of oscillation is 2 times. Depth of main fatigue crack at this point ranged from 1/2 to 2/3 the sample thickness.

The AE activity analysis of various fatigue stages was carried out after division of signals into types of the AE sources. Division of the AE signals was carried out on the plane of two-parameter distribution: the energy of AE signals vs the frequency coefficient (E-K_f) [6, 7]. On the diagrams distribution E-K_f identified three areas corresponding to the different types of the AE sources (fig. 2.): dislocation sources (1), the formation and development of microcracks (2), and macrocracks (3).

![Figure 2](image-url)

The choice of the boundaries was based on multiple experimental studies of samples of different materials under static and cyclic tests. As signals at formation of macrocracks it was
considered to be AE signals registered at formation of new surfaces with an area of disclosure more than 1000 μm².

Selections allow to evaluate the participation of various types of registered sources in the accumulation of fatigue damage. The widest dispersion E-K value distribution observed for samples with MC structure. This is natural, given the method of formation of structure of the samples by partial annealing. Firstly, the grain growth as a result of polygonization boundaries by thermal annealing leads to the formation of different grains sizes. This entails an uneven fatigue micro- and macro-cracks. Secondly, the annealed material rapidly hardened under cyclic deformation, forming a structure with local differences in properties. Existence on the samples fracture with GC structure various width and directions fatigue grooves to confirms irregularity of deformation (fig. 3, a).

Microcracks are distributed mainly along the grain boundaries and have irregular branching. Separate building with total AE schedules by type of AE sources revealed Activity AE accumulation of fatigue damage at various stages of fatigue. The separation stage was carried out based on the estimation of total AE graphs for different types of sources. Numbering stages preserved regardless of their presence. The entire period of the fatigue damage accumulation to includes six stages: I - cyclic microfluidity, II - cyclic yield strength, III - cyclic hardening, IV - the microcracks birth and propagation to the size of the submicrocracks, V - propagation of the microcracks to the size of the macrocracks, VI - stage of the rupture area.

All the stages except for stage VI are present in the graphs of the total AE accumulation (fig. 4). These stages can be observed on the samples annealed MC structure. Stage VI (rupture area) usually short and is a few tens of cycles. Stage I-III relate to the incubation period. You can distinguish them by activity signals of the dislocation type.

Stage I (cyclic microfluidity) is characterized by low AE activity of dislocation type. The transition to stage II is accompanied by increased activity of AE signals dislocation type. This is due to the onset of the total yield strength of the material throughout the volume of the loaded parts of the sample. It should be noted that the transitions from stage to stage during bending deformation are longer and tend to overlap in connection with the uneven stresses in the sample section.

For this reason, the stage of cyclic yield stress and cyclic hardening at the AE activity is not always distinguishable. In the transition from yield stage III which completes the incubation period to stage IV, the dislocation type activity of AE signals is not reduced or not reduced.
The beginning of stage IV is always characterized by increasing activity of AE signals (2) emitted from the microcracks. For samples with MC structure, the proportion of the total duration of stages II to IV amounts to 20 - 25 % of the total durability $25\cdot10^3 - 35\cdot10^3$ cycles. Duration stages II-IV in the sample with UCG structure is reduced to 3 - 6 % due to a reduction in the overall ductility. The reduction of the overall ductility caused by increase of density of defects and the nonequilibrium structures that the resulting ECAP. In samples with SMC structure are characterized by an even greater decrease in the proportion of stages II-IV up to 0.1 %. A significant decrease of the mean free path of the dislocations reduces the level of the emitted energy. The width of fatigue grooves in the samples with SMC structure is not more than 100 nm, but in samples with a CG structure is about 500 nm.

However, the energy of registered AE signals of larger value has a length of fatigue grooves, which are determined by the size of the grains. The energy induced by the defect of the elastic wave depends on the speed of movement and parameters of the defects and is defined as

$$E=A \cdot \rho \cdot S \cdot L \cdot V^2,$$

where $A$ is a coefficient depending on the properties of the material, $\rho$ is the material medium density, $S$ - the area of the formed of the defect surface, $L$ - the characteristic size of the defect or the degree of the opening cracks, $V$ – the velocity of the defect.
At constant values of $\rho$, $V$ and the grain size calculated value of the energy of AE signal, which is excited by a increment of the single fatigue grooves in one grain with CG structure, more so for the SMC structure more than 500 times. Diagram fig. 4 (a) demonstrates the registration of a large number of AE signals (3) (fig. 2) with an energy of more than 1.8 mB^2c in the test sample with SMC structure. In confirmation of this on the fracture surface of sample with SMC structure it is possible to observe a large number of normal to the surface cracks of the fracture with opening width of 0.5 µm.

Most of the AE signals is related to the type (3) (fig. 2) is recorded at stage V. However, the origin of main crack occurs earlier. The main part of the AE signals at its origin are signals emitted by the areas of microplastic deformation and microcracks. However, the absence of AE signals in the early stage of origin the main cracks is due to the low value of their energy in connection with small sizes of the emitting AE sources. AE signals with high values of energy begin to occur only at the stage of pre-destruction and destruction.

For registration of the AE signals in the early stages of damage accumulation in samples with SMC structure, it is necessary to improve the sensitivity of AE equipment. It is often associated with certain difficulties related to the presence of noise.

The grain boundaries have a great influence on the damage accumulation and the processes affecting the change of properties under static and cyclic loads. Refinement of the structure leads to increase of durability of the samples in the SMC as compared to the original CG structure. But be aware that severe plastic deformation leads to a significant increase of the grain boundaries energy, which leads to facilitation of the microcracks formation due to accumulation of defects at the grain boundaries. Thus, in the studied materials the grain boundaries are sources of destruction, because on the grain boundaries are emerging and evolving microcracks.

**Conclusions**

1. The nature of AE count accumulation of different types of AE signals sources (dislocations, micro- and macro-cracks) is set stepwise nature of fatigue damage accumulation of commercial titanium VT1-0 in different structural states. Six stages of fatigue accumulation have been revealed.
2. The accumulation periods of total AE of various types of AE signals sources by the bending test are always overlap. This is mainly due to the uneven stress over the cross section of the sample and sequential shift stratified period of the offensive and of the end of each stage.
3. Reduction of grain size in the restructuring from CG structure to SMC structure leads to a reduction of radiated energy signals in steps II-IV, identified by AE parameters. This results lead to later detection of the stages and reduction in the extent of total durability for the test of specimens with the SMC structure as compared with the of UFC and CG structure.

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**References**
