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The study of dilatation evolution and elastic properties degradation in metals under deformation in gigacycle fatigue regime

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ABSTRACT

The work is devoted to the study of evolution of dilatation and elastic properties in metals under deformation in the gigacycle fatigue regime. The deformation process was realized in the ultrasonic testing machine Shimadzy USF-2000. Two sets of samples at different loading times were investigated based on the hydrostatic weighing method and the acoustic resonance method. The proposed techniques were verified using Armco iron samples and then were applied to study the evolution of defects in sub-microcrystalline titanium Grade 4. The obtained results showed that fatigue loading leads to accumulation of porosity in the samples and a corresponding decrease of their elastic properties. This effect was simulated using a statistical model of defect accumulation, which revealed the influence of the sample surface on the fatigue crack initiation sites.

1. Introduction

Nowadays an increasingly growing interest is being shown in the study of fatigue behavior of metals in gigacycle fatigue regime (often referred to as very high cyclic fatigue) longer than 10^7 cycles [1–18]. Such tests with a number of loading cycles of 10^8–10^{10} are generally performed on the ultrasonic fatigue testing machine [2]. The initial fatigue tests were carried out in the symmetrical pull–push loading regime [1–3]. More recently, the experimental setups were modified to study the fatigue behavior under non zero mean stress [4] and under torsion loading [5].

Fractography of the fracture surface structure shows that inclusions play an important role in the process of fatigue crack initiation in steels [5–8]. Generally the fractography of fracture surfaces singles out three areas of different roughness [7]. The zone of crack initiation is characterized by high concentration of defects, small grain size and centered inclusion. The typical size of this zone is about several tens of microns. Generally this area is called FGA – the fine granular area (in the literature there are also such abbreviations as ODA-optical dark area, GBF-granular bright facet). The size of FGA decreases with increase of the applied stress amplitude, so that the stress intensity factor (SIF) on the FGA boundary remains constant [4,7]. The value of SIF is less or equal to the threshold value, at which the fatigue crack propagation occurs in the Paris regime. The second area is smooth and develops into a rough surface with characteristic traces of radial cracks. The formation of FGA under the sample surface is one of the most issue for the development of gigacycle fatigue [7,9].

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Nomenclature

σ	applied stress amplitude
E	Young's modulus
ρ	density
l	sample length
S	cross sectional area
μ	Poisson's ratio
I	moment of inertia of the sample relative to its longitudinal axis
n	harmonic number
ν	loading frequency
ν_1	pieze quartz frequency
ν_2	frequency of the system – piezo quartz and sample
m_0	weight of the sample
m_1	weight of the pieze quartz
δ	amplitude independent decrement
l_p	Onsager coefficient
F	specific free energy
D	coefficient of self-diffusion
E_{sd}	activation energy of self-diffusion
T	temperature
V_{sur}, V_{bulk}	representative material volumes
p_0, l_p, a	material constants
h	the constant which determines the boundary conditions for considered volumes
τ, n', Ψ, h'	dimensionless variables
t_f	critical time (life time)

A lot of attempts have been undertaken to describe the physics of FGA initiation [6,9–17]. A qualitative mechanical model describing the formation of FGA was proposed in [7]. The first stage of FGA formation is related to the emergence of fine granular layer due to intensive polygonization around the inclusion during a long-term cyclic loading. During the second stage the number of micro-debondings gradually increases and some of them coalesce with each other (nucleation and coalescence of micro-debondings). At the final stage the micro-debondings are entirely spread over the fine granular layer, which leads to the formation of penny-shape cracks.

A model of FGA formation proposed in [10] is based on the dispersive decohesion of spherical carbides in the neighborhood of non-metallic inclusions. A mechanism of FGA formation associated with extremely slow fatigue crack propagation in the Paris regime was proposed in [11]. The model of FGA formation based on the analysis of hydrogen embrittlement in the vicinity of inclusions was proposed in [12]. A model for predicting the fatigue life of high strength steels based on the Paris law and generalized dislocation model of crack initiation were proposed in [6]. To assess the fatigue life of high strength steels subjected to gigacycle fatigue loads the researchers use the models that are based on the empirical correlation and include the dimensions of FGA, inclusion and the number of cycles [13] and as well as the probabilistic models of crack growth [14]. Some other models of fatigue crack initiation in gigacycle fatigue regime were proposed in [15–17].

Another interesting and important aspect of the problem is the fatigue behavior of sub-microcrystalline metals under gigacycle fatigue loading regime [18]. These materials are characterized by high concentration of sub-micropores (0.1–0.3 mkm) [19]. This allows us to hypothesize the important role of these defects in the process of cyclic deformation of sub-microcrystalline metals in the gigacycle fatigue regime.

One of the possible tools for description of defect kinetics is the statistical model of defect ensemble [20]. This model takes into account the stochastic properties of defect initiation, their nonlinear interactions and links between microplasticity and damage accumulation.

To gain a reliable experimental basis for this model we have investigated the evolution of the dilatation and elastic properties in sub-microcrystalline titanium Grade 4 samples loaded in gigacycle fatigue regime. A similar study for extruded pure magnesium was carried out in [21]. To verify the experimental technique and to generalize the obtained peculiarities we developed and implemented the second experimental program, in which the well-studied [22] and relative cheap Armco iron was used.

The experiments were performed on the Shimadzu USF-2000 testing machine. We investigated the mechanical properties (elastic modulus, amplitude-independent damping) and dilatation for a set of samples with different degrees of the life time exhaustion. The study of mechanical properties was carried out based on the acoustic resonance method using a piezoelec-

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