FRACTURE PECULIARITIES OF NITINOL UNDER LOW-CYCLE FATIGUE

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The features of fracture of shape memory alloy samples (nitinol) under low-cycle fatigue with different load frequencies were investigated. The frequency dependences of such indicators as the number of cycles before the destruction of the samples, and the maximum and residual deformation, respectively, before and after their destruction, were analyzed. It is shown fractographically that the mechanism of fatigue failure of specimens depends on the frequency of loading.

Keywords: shape memory alloys, nitinol, fatigue tests, fracture, fractography

Introduction. The shape memory alloys (SMAs) are functional materials, which can be applied in many applications, namely automotive, aerospace, wearable, mobile robot, robotic hand, bio-medical, etc. SMAs are widely used due to the phenomenon of phase transformation and their inherent effect of shape memory and effect pseudo elasticity [1]. The SMAs can return to their original geometry, even after reaching large inelastic deformations, up to 10% strain. The shape memory effect and super elasticity provide SMAs with a high ability to dissipate energy and therefore they are widely used in materials operated under the influence of cyclic loads. Phase transformations (direct austenitic-martensitic and reversed martensitic-austenitic) in SMAs can be activated by heating or loading (Fig. 1). Therefore, it was assumed that the mechanism of propagation of fatigue failure in these alloys should differ from that in other materials.

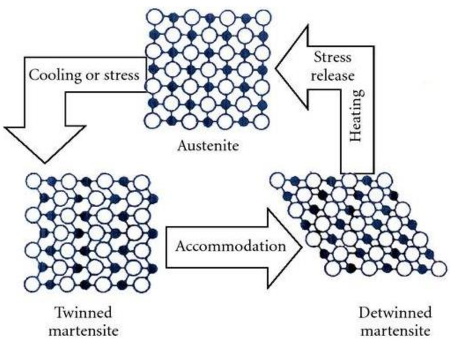


Fig. 1. Scheme of transformations of the crystal lattice in SMAs [1].

Material and methods. Nitinol samples $Ni_{55.8}Ti_{44.1}$ with a length and diameter of 210 and 1.5 mm, respectively, was studied under cyclic tension with a strictly controlled range of stresses and different cycle frequencies (from 0.1 to 10 Hz) with a stress ratio equal to 0.1.

Fatigue tests were carried out on the SMT-100 servo-hydraulic testing machine using the Test Builder software. During the tests, the applied load and corresponding elongation of the samples were recorded. The elongation values were measured by an extensometer. Fractographic peculiarities of the tested samples were evaluated using a scanning electron microscope.

Results and discussion. Hysteresis loops were fixed on the dependences between stress and strain in each of the loading cycles of the samples. It was used to estimate the energy W_{dis}, which was dissipated (most often in the form of heat) and not spent on the deformation of the sample. Its value in each load cycle was determined by numerical integration using the trapezoidal method as a difference in areas under the stress-strain curves in half-cycles of loading and unloading, respectively. The typical hysteresis loops of stress (σ) – strain (ε) of nitinol wire samples obtained in the tenth, hundredth and thousandth loading cycles at various frequencies were obtained. With an increase in load cycles N and frequency f, the stress range changed slightly (until it stabilized after 10-100 cycles) as well as the shape and slope of the hysteresis loops. The dependences of the dissipated energy W_{dis} on several loading cycles N for nitinol samples tested at various loading frequencies were obtained. The dependence of the change in the maximum values of the dissipated energy W_{dis}^{max} during the tests on the frequency of load cycles is plotted. One can notice the change in the slope of this curve at 1 Hz (Fig. 2).

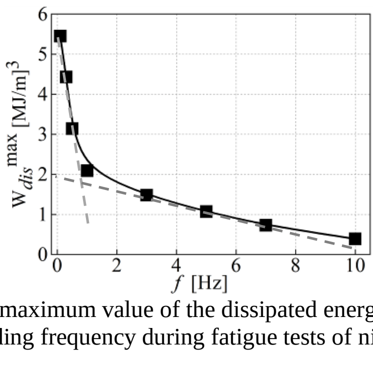


Fig. 2. Change in the maximum value of the dissipated energy W_{dis}^{max} depending on loading frequency during fatigue tests of nitinol.

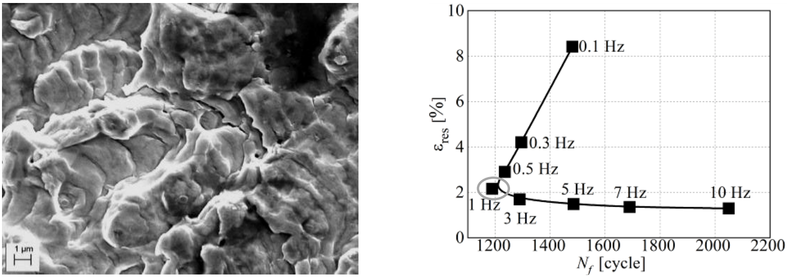
The influence of loading frequency f during fatigue tests of nitinol on the maximum deformation ε_{max} of the samples until their fracture, residual deformation ε_{res} after their fracture, and the difference between them that characterizes an elastic deformation released at the moment of fracture were defined. All deformation indicators decrease exponentially as f increases. Moreover, the inflection point on each dependency corresponds to the test at 1 Hz. Localization of deformation should contribute to martensitic transformation into nitinol stimulated by stress and, accordingly, to the weakening of the pre-fracture zone at low loading frequencies. However, the fatigue life of nitinol at frequencies up to 1 Hz was slightly higher. An increase in frequency *f* from 1 to 10 Hz accompanied by an extension of the fatigue life. The obtained inversion of the influence of frequency *f* can be explained by the further temperature rise of a sample and, thus, the impossibility of the temperature-induced martensitic transformation in the pre-fracture zone of the samples tested at a higher frequency. In this case, only the deformation of nitinol with austenite structure is manifested, which usually dominates it at elevated temperatures.

Fractographic analysis of nitinol samples after fatigue tests was carried out, and typical fracture zones were distinguished. Micro fractograms of the crack initiation zone from the side surface of a sample, tested at a frequency of 0.1 Hz were analyzed. Festoons are a typical fractographic feature after fatigue tests, oriented in the direction of fatigue crack growth. Fatigue striations are usually detected across the festoons, but within the crack initiation zone in nitinol due to the contact of the crack edges behind its tip, their signs on the fracture surface were destroyed. Fractures surface of samples tested at a frequency of 1 and 10 Hz were also analyzed. Distinct rows of two types of fatigue striations were found across individual festoons. They differed both in the spacing size (for some it was narrower, for others it was wider) and in the slope relative to the direction of crack propagation. The average space of the wider striations is 0.5 μm, and the narrower ones – 0.2 μm. Since the spacing of striations corresponds to the crack increment in each loading cycle, the crack growth rate ($6{\cdot}10^{-7}$m/cycle) at this stage is evaluated.

The fracture surfaces of nitinol samples in the subcritical fracture zone were analyzed. Festoons of different shapes are oriented predominantly in the main direction of crack propagation, regardless of loading frequency. Festoons with transverse fatigue striations are quite distinct; the striation spacing is approx. 0.9 μm. The peculiarity of festoons in nitinol is their convex (or concave) surface, whereas in steel they are mostly flat. Such fracture relief with fatigue striations of variable spaces is explained by shear along different planes at the crack tip, as a result of multiple direct and reverse structural phase transformations in nitinol, initiated by stress changes in its loading cycle.

In the final fracture zone, a ductile microrelief was observed on all fracture surfaces of nitinol samples. Parabolic dimples were formed due to the nucleation and growth of pores with the stretching of bridges between them.

So, for the tests at frequency $f \leq 1$ Hz, a new type of fatigue striations is detected, characterized by alternate changes in the spacing of striations with loading cycles (Fig. 3*a*). They occurred due to favourable conditions for shear along different planes in the crack tip during phase transformations in a loading cycle, direct (austenite → martensite) and reverse (martensite → austenite).



a b

Fig. 3. The fractogram of the fatigue fracture surface of nitinol with striations at different spacing sizes (a) and dependence of the residual deformation after fracture ε_{res} on several loading cycles N_f until the fracture (b).

Figure 3, b presented the dependence of the residual deformation after fracture ε_{res} on several loading cycles until the fracture. The deformation mechanisms are different for the two sections of the curve. If the frequency *f* is lower than 1 Hz, the residual deformation of the sample increases significantly, which may be due to phase transformations of austenite into martensite (and vice versa), activated by a change in stresses in the pre-fracture zone in the loading cycle. If frequency *f* is greater than 1 Hz, ε_{res} almost independent of frequency *f*, apparently due to the invariance of the nature of austenite deformation at elevated temperature of a sample during tests in this frequency range.

Conclusions. Fatigue tests of SMA (nitinol) wires showed that the deformation indicators (maximum dissipated energy $W_{dis}^{\max}$, maximum ε_{max}, and residual ε_{res} deformation) decrease with the rise of loading frequency *f* from 0.1 to 10 Hz. The fatigue life of nitinol decreases at frequencies from 0.1 to 1 Hz as well as residual deformation ε_{res}; however, further increase in *f* up to 10 Hz leads to significant fatigue life extension despite a slight change in ε_{res} of the samples. Fractographic studies revealed the signs of the fatigue fracture mechanism in the form of festoons elongated in the direction of crack propagation and fatigue striations across them regardless of loading frequency. A specific type of fatigue striations was found during the fracture of samples tested at a frequency $f \leq 1$ Hz. Its peculiarity lies in the alternating change in the space of the fatigue striations in each loading cycle. This is possible due to favorable conditions for shear along different planes at the crack tip due to various phase transformations: direct (austenite → martensite) in the loading half-cycle and reverse (martensite → austenite) in the unloading half-cycle.

1. *Fernandes D. J., Peres R. V., Mendes A. M. and Elias C. N.* Understanding the Shape-Memory Alloys Used in Orthodontics. – ISRN Dent. International Scholarly Research Network., 2011. – 2013. – No. 132408.