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METHODOLOGY AND SOME RESULTS OF STUDYING THE INFLUENCE OF FREQUENCY ON FUNCTIONAL PROPERTIES OF PSEUDOELASTIC SMA

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Summary. *The mechanical loading frequency affects the functional properties of shape memory alloys (SMA). Thus, it is necessary to study the effect of frequency in order to use successfully these materials in real structures. Based on the pseudoelastic cyclic behavior, the experimental methodology that allows testing of NiTi wires in stress controlled mode is proposed. Cyclic tensile tests are carried out using universal testing machine STM-100 at room temperature with loading frequencies of 0.1 Hz and 10 Hz. The functional dependencies are determined based on the experimentally obtained hysteresis loops. These functional dependencies comprise dissipated energy and damping factor. It iis found that the increase of loading frequency results in the worsening of functional properties, namely, to the decrease of dissipated energy and damping factor. This is caused by the fact that the regions of austenitic and martensitic transformation under the high loading frequency are absent. That is, the transformation of austenite into martensite does not occur, that stands for the pseudoelasticity effect. Nevertheless, it should be noted that the increase of loading frequency in 100 times augments the lifetime of pseudoelastic wire made of NiTi alloy roughly by 30%. It is determined that the increase of loading frequency results in the decrease of maximum strain in two times in the first loading cycle, and practically in 5 times after 200 cycles of loading.*

Key words: *pseudoelastic NiTi wire, cyclic loading, frequency, functional properties.*

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Statement of the problem. Alloys with shape memory are functional materials that are mostly exposed to vibration and dynamic loads, the influence of climatic temperatures, variable frequency and load amplitude during operational and seismic loadings. In order to ensure the necessary parameters of damping devices, it is necessary to carry out complex experimental and computational studies of changes in mechanical and functional properties of SMAs and damping devices [1], [2], taking into account the fact that most pseudo-elastic SMAs used in structures or devices, are exposed to cyclic loads with variable frequency.

Analysis of available investigation results. Well-known papers are devoted to the investigation of the load frequency influence on deformation, load amplitude or temperature [3], [4], [5]. There are certain papers where finite element analysis is used for modeling the influence of loading frequency of the sandwich-plate with composite sheets built-in in pre-tensioned SMA wires [6]. The results show that with the temperature increase, the natural frequencies of sandwich plates decrease due to the deterioration of functional properties of pseudoelastic SMA. Under cyclic loads, the heat generated during direct and reverse phase transformations in SMA, caused by accumulated stress is in the samples.

While investigating the conical spring washer made of SMA, which was previously compressed during 50 cycles under controlled deformation, it was established that with the increase of load frequency from 0.5 Hz to 10 Hz, the energy dissipated per cycle and equivalent viscous damping factor decrease, and stiffness increases. At the same time, it should be noted that the equivalent viscous damping factor and energy dissipated per cycle decrease with the increase in the number of load cycles at load frequencies 0.5 Hz, 1 Hz and 2 Hz. However, within the frequency range from 3 to 10 Hz, first, there is a slight decrease in energy dissipated per cycle, whereupon it sharply increases after 10-20 load cycles (it is clearly visible at 10 Hz frequency, and then reaches the plateau and remains practically unchanged [7].

The objective of the paper is to identify the main regularities of the load frequency influence on functional properties of SMA under soft load mode.

Statement of the problem. Since the most known papers either propose theoretical approaches and model the analysis of load frequency influence on functional properties, or carry out investigations under controlled strain, it is important to determine these regularities experimentally under controlled stress.

The load frequency influence on the functional properties of the shape memory alloy was investigated. The 1.5 mm wire in diameter made of $Ni_{55,8}Ti_{44,2}$ alloy (manufactured by Wuxi Xin Xin glai Steel Trade Co., LTD) was used in this experiment. The gauge length of the wire was 210 mm. The modulus of elasticity of the wire in austenite phase E_A = 52.7 GPa, the stress at the beginning of transformation σ^{AM} = 338 MPa [8].

The investigation was carried out at room temperature on the STM-100 servo-hydraulic machine. Uniaxial tensile test were performed under sinusoidal cyclic loading in stress-controlled mode. Test were carried out at frequencies 0.1 Hz and 1 Hz and stress ratio in both cases was R_σ = 0.1.

Figure 1. Working fixation of wire and extensometer for measuring longitudinal strain on STM-100 testing machine

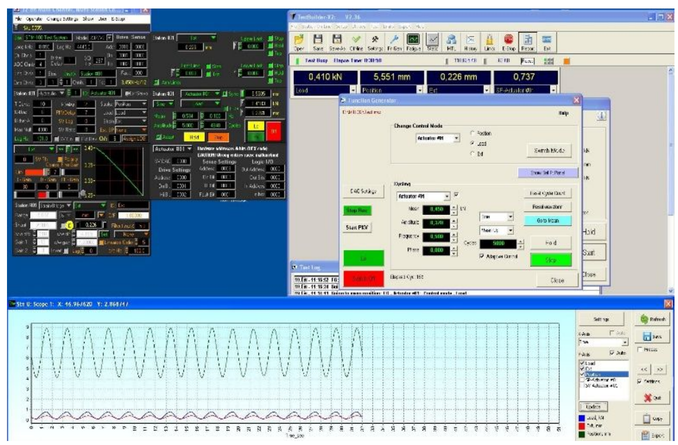

Figure 2. Form of loading cycle at frequency 0.5 Hz in Test Builder, which is used to control and record data from STM-100 testing machine

During the test loading, displacement and longitudinal strain of the wires were recorded. The elongation was measured by the extensometer of Bi-06-308 model produced by BISS, the maximum error did not exceed 0.1%. The displacement was measured by inductive Bi-02-313 sensor with the error that did not exceed 0.1%. Stresses and strains were determined by values (force-elongation) obtained from Test Builder program. Energy dissipated per load cycle were determined by hysteresis loops using trapezium method according to formula (1):

$$W_{dis\,i} = W_{dis\,i-1} + \frac{1}{2}(\varepsilon_i - \varepsilon_{i-1})(\sigma_i + \sigma_{i-1}), \qquad (1)$$

where W_{dis} is dissipated energy, MJ/m^3; ε is relative deformation, m/m; σ is stress, MPa.

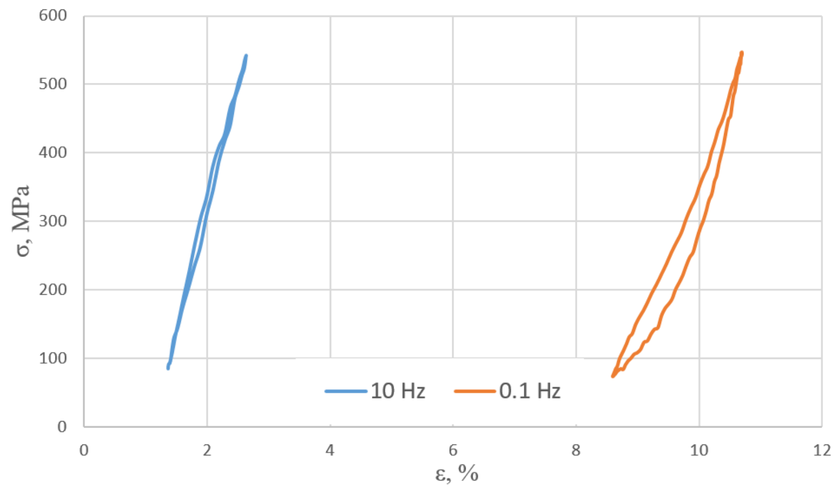

Figure 3. NiTi alloy hysteresis loop of the 1000th load cycle at frequency 0.1 Hz

The increase in load frequency from 0.1 Hz to 10 Hz results in the change of hysteresis loop of pseudoelastic SMA, namely, in the decrease of its area and practically triples the dissipated energy in the first load cycle. The dissipated energy increases during the first 40 cycles at 0.1 Hz load frequency.

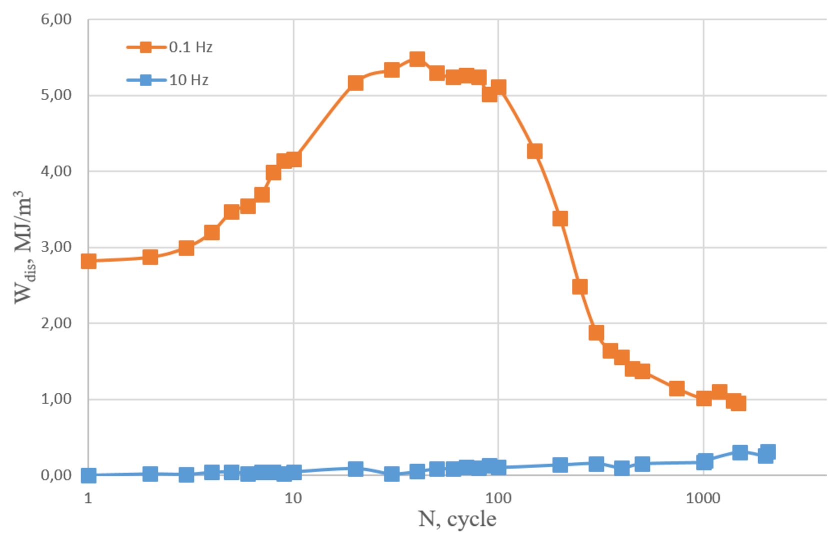

Figure 4. The dependencies of dissipated energy of NiTi alloy on the number of load cycles

For each load cycle, the damping coefficient (2) is determined and its dependence on the number of load cycles is plotted:

$$\eta = \Delta W / \left(\pi (2W - W_d)\right) \qquad (2)$$

As in the case of dissipated energy, the damping coefficient can be characterized in a similar way, since these two parameters depend on the hysteresis loop area. The damping coefficient significantly decreases at frequency of 10 Hz, and increases at frequency of 0.1 Hz. Despite this, at both frequencies the coefficient reaches the plateau until fracture.

Degradation of functional properties with the increase of load frequency, a decrease in dissipated energy and damping factor, is due to the absence of austenitic-martensitic transformation, which is responsible for the pseudoelastic effect. Thus, at 10 Hz load frequency, there are no forward (austenitic-martensitic) transformation sections on the deformation diagrams. On the other hand, the increase of load frequency results in faster heating of the sample, which in turn shifts the stress of austenitic-martensitic transformation.

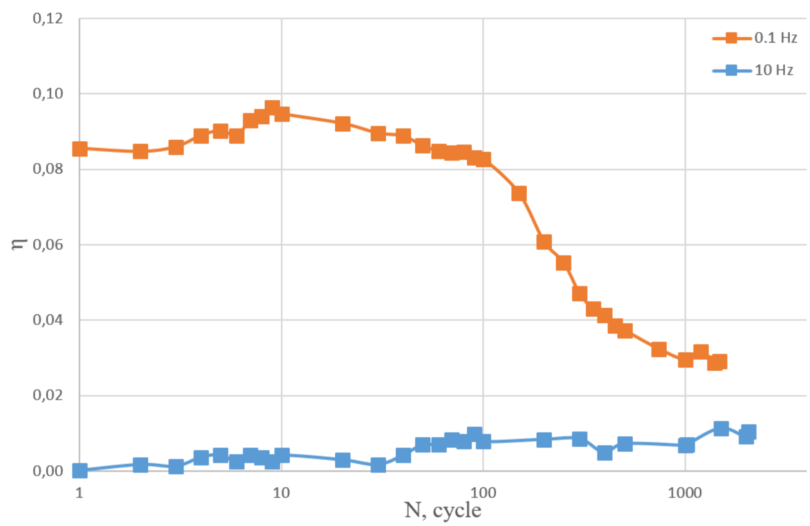

Figure 5. Dependence of the energy damping coefficient on the number of load cycles

It should be noted that 100 times magnification of load frequency increase the durability of pseudoelastic wire made of NiTi alloy by approximately 30%. At 0.1 Hz load frequency, the wire fractured after 1477 cycles, and at 10 Hz frequency – after 2052 cycles.

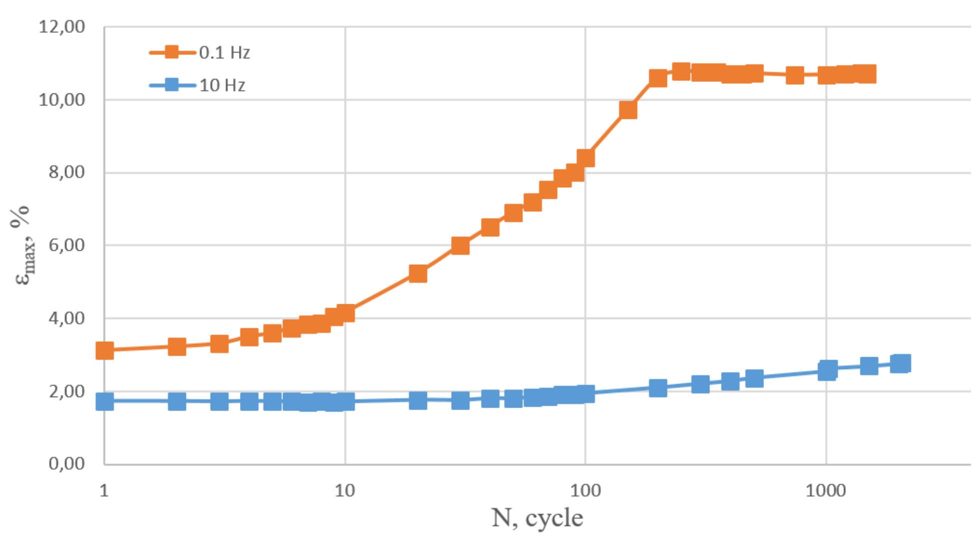

Figure 6. Dependencies of the maximum deformations of NiTi alloy on the number of load cycles

From the dependence of the maximum deformations on the number of load cycles, it is evident that the increase in load frequency results in the decrease of maximum deformations in the first cycle by approximately 2 times, and after the 200th load cycle - by almost 5 times. After the 200th cycle, the maximum strain remains constant at 0.1 Hz frequency, but continues to increase at 10 Hz frequency.

Analysis of the obtained results and the behavior of pseudoelastic wire made of NiTi alloy with 1.5 mm diameter requires deeper investigations of the material before its application in real structures, since the load frequency significantly affects the functional properties and the pseudoelastic effect under controlled loading mode.

Conclusions. A set of 1.5 mm diameter pseudoelastic NiTi wires were tested under tensile cyclic loading at two different frequencies. The increase in the load frequency leads to the absence of austenitic-martensitic transformation area, which is responsible for the effect of pseudoelasticity. The absence of such an area on the deformation diagram at 10 Hz frequency reduces the area of hysteresis loop and degradation of the functional properties, dissipated energy, and damping factor. With the frequency increase from 0.1 Hz to 10 Hz, the number of cycles to failure also increases under soft load mode.

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МЕТОДИКА ТА ДЕЯКІ РЕЗУЛЬТАТИ ДОСЛІДЖЕННЯ ВПЛИВУ ЧАСТОТИ НАВАНТАЖЕННЯ НА ФУНКЦІОНАЛЬНІ ВЛАСТИВОСТІ ПСЕВДОПРУЖНОГО СПФ

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Резюме. *Значення частоти за механічного навантаження впливає на функціональні властивості сплавів з пам'яттю форми (СПФ). Саме тому необхідно вивчити вплив частоти, щоб успішно використовувати ці матеріали в реальних будівельних конструкціях та спорудах. Більшість праць опираються на дослідження із жорстким режимом навантаження (контрольовані деформації зразка). Тому на основі псевдопружної циклічної поведінки запропоновано експериментальну методику, яка дозволяє перевіряти дротину зі сплаву нітинолу (NiTi) у м'якому режимі навантаження (контрольовані напруження у зразку). У досліді скористалися дротиною діаметром 1,5 мм зі сплаву нітинолу* $Ni_{55,8}Ti_{44,2}$. *Робоча довжина дротини складала 210 мм. Модуль пружності дротини в аустенітній фазі* $E_A = 52,7$ *ГПа, напруження початку перетворення* $\sigma^{AM} = 338$ *МПа. Циклічні випробування на розтяг проводили на універсальній випробувальній машині STM-100 при кімнатній температурі з частотою навантаження 0,1 Гц та 10 Гц. Коефіцієнт асиметрії циклу навантаження становив* $R_\sigma = 0,1$. *Функціональні залежності визначені на основі експериментально отриманих петель гістерезису. Ці функціональні залежності містять дисиповану енергію та коефіцієнт демпфування. Встановлено, що збільшення частоти навантаження призводить до погіршення функціональних властивостей, а саме, до зменшення розсіюваної енергії та коефіцієнта демпфування. Це пов'язано з відсутністю областей аустенітного й мартенситного перетворень за високої частоти навантаження. Тобто перетворення аустеніту в мартенсит, що є умовою ефекту псевдопружності, не відбувається. Тим не менш, слід зазначити, що збільшення частоти навантаження в 100 разів збільшує термін служби псевдопружного дроту зі сплаву NiTi приблизно на 30%. Визначено, що збільшення частоти навантаження призводить до зменшення максимальної деформації приблизно в два рази в першому циклі навантаження, і практично в 5 разів після 200 циклів навантаження.*

Ключові слова: *псевдопружна NiTi дротина, циклічне навантаження, частота, функціональні властивості.*

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