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МЕХАНІКА ТА МАТЕРІАЛОЗНАВСТВО

UDC 539.3

MODELLING OF MECHANICAL BEHAVIOUR OF SHAPE MEMORY ALLOYS USING FINITE ELEMENTS METHOD

Petro Yasniy; Oleksandr Dyvdyk; Nadiia Lutsyk; Volodymyr Yasnii

Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine

Summary. *Superelastic behaviour of Ni-Ti alloy wire under variable amplitude loading was simulated and experimentally studied. Mechanical properties and phase transformation stresses (*σ^{Ms}*,* σ^{Mf}*,* σ^{As}*,* σ^{Af}*) of the material were obtained in uniaxial tensile test. The wire of 55,8% Ni – 44,2% Ti alloy with a diameter of 1,5 mm and a working length of 30 mm was tested at room temperature (+ 16°C) on the air. On the base of finite elements method, using ANSYS the stress-strain dependencies on each loading cycle were calculated. The stress-phase transformation are changes under a variable amplitude loading. The simulated stress-strain dependencies were compared with the experimental ones. The maximum error, being compared with experimental data, does not exceed 10,9%. The calculated dependences of elastic strain and dissipated energies on the amplitude stress are well agreed with experimental data. The obtained results are of theoretical and applied interest for modelling the superelastic behaviour of SMA under variable amplitude loading.*

Key words: *shape memory alloy, superelastic, stress-phase transformations, martensite, austenite, energy dissipation.*

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Statement of the problem. Development of science and technology promotes the appearance of new and advanced requirements for application of materials, their strength and durability characteristics. Shape memory alloys (SMA) are used in many branches of industry thanks to the shape memory effect, good damping properties, durability and strength characteristics [1 – 6]. The nickel-titanium alloy can «remember» its original shape and return it in the original non-deformed state after unloading (the effect of pseudoelasticity) or heating (the effect of shape memory) during many cycles of loading and unloading.

Analysis of available results of investigations. The shape memory alloy Nitinol – (Ni-Ti) was created in the 1960-ies at Naval Ordnance Laboratory (USA) and soon was widely used in medicine and different branches of engineering [1 – 4]. Many papers are devoted to the pseudoelesticity modelling and the shape memory effect of such alloys, the study of which is presented in the paper [7] in particular. The 3D model of the shape of the shape memory alloys behaviour for ANSYS makes possible to take into account the decrease of rigidity of the structural element during transition from austenite to martensite [8]. The 3D SMA model [9], which presents the pseudoelestic behaviour and the shape memory effect and makes possible to model, using the finite elements method, the behaviour of free-extended stents and spring working elements, is presented.

The Objective of the paper. To model the pseudoelastic behaviour of nickel-titanium alloy, using the finite elements method (FEM), under the variable amplitude of loading and compare it with the experimental results.

Statement of the task. Mechanical behaviour of SMA is specified by the microstructure characteristics, containing two different phases, austenite and martensite.

Corresponding author: Oleksandr Dyvdyk; e-mail: SashaDyvdyk@gmail.com

When loading is above the temperature of the austenite transformation finish, the effect of so-called pseudoelasticity is revealed (Fig. 1) [10]. Under the tensile strain austenite is transformed into martensite (forward phase transformation), under the unloading martensite in transformed into austenite.

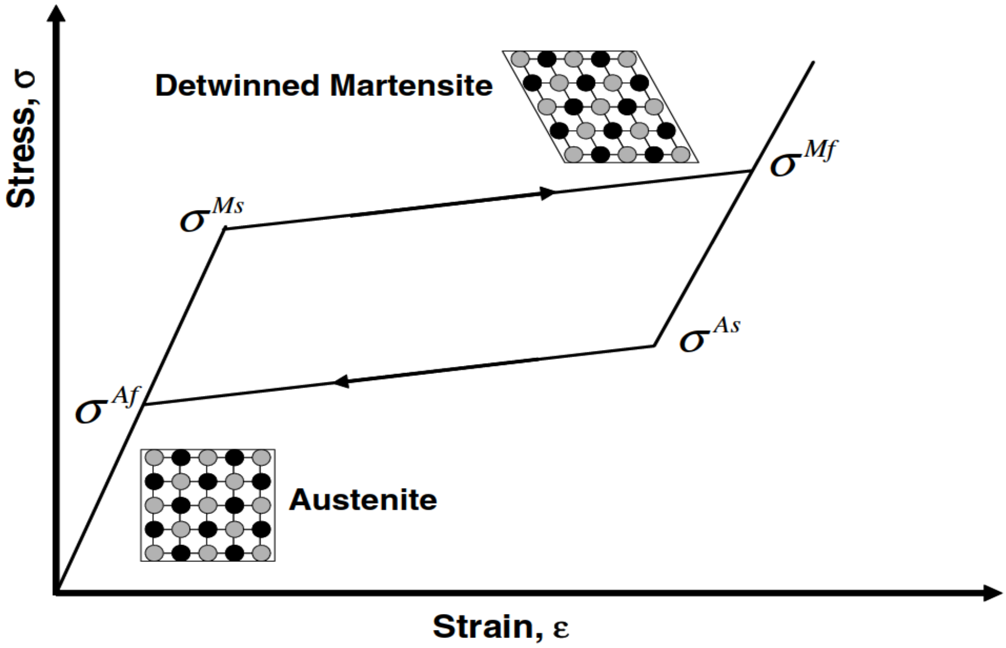

Figure 1. Ideal curve of pseudoelastic behaviour, where σ^{Ms}, σ^{Mf} – are stress start and finish of phase transformations of martensite; σ^{As}, σ^{Af} – are stress start and finish of phase transformations of austenite [10]

The stress, under which the martensite transformation starts and finishes, are marked as σ^{Ms} and σ^{Mf}. Similarly, under unloading the stress values, at which the start and finish of the inverse martensite transformation in austenite take place, are marked as σ^{As} and σ^{Af} correspondingly. The phase changes, taking part in the pseudoelastic behaviour, are the transformations of austenite in martensite under loading, martensite in austenite under unloading and the martensite reorientation. The material being loaded till the stresses exceeding the yield limit, can recover totally its original shape after unloading and return to the original shape after unloading and return to the original non-deformed state. The pseudoelastic behaviour is revealed in the range of temperatures between the start of forward phase transformations and the finish of the inverse phase transformations or as a result of mechanical loading [7, 10].

Taking advantage of FEM the pseudoelastic behaviour of the nickel-titanium alloy under the cyclic tensite strain was modeled. The finite elements 3D model was created in the software complex ANSYS Workbench.

While modelling the mechanical property characteristics of the nickel-titanium alloy obtained experimentally were used [11]. The pseudoelastic behaviour of the nickel-titanium alloy under random loading was modelled. The results of numerical modelling are well agreed with the experimental data, obtained by the authors under the uniaxial tensile strain and unloading of the cylinder specimens made of nickel-titanium alloy at the temperature exceeding the temperature of the austenite phase transformation finish.

Method of investigation. In the paper the characteristics of mechanical properties (Table 1) of the nickel-titanium alloy Ni-Ti *(Ni – 55,8%, Ti – 44,2%)* [11], obtained experimentally, were used, stresses of forward (σ^{Ms}, σ^{Ms}) and inverse (σ^{As}, σ^{Af}) austenite martensite phase transformations at the temperature *16°C* in particular have been used. The cyclic loading was performed by the updated machine FP-100 at the maximum stress *100 kN* under the uniaxial tensile of the *1,5 mm* diameter wire.

Table 1

Physical-mechanical properties of the material

Starting stress value for the forward phase transformation, σ^{Ms}	MPa	450
Final stress value for the forward phase transformation, σ^{Mf}		460
Starting stress value for the reverse phase transformation, σ^{As}		190
Final stress value for the reverse phase transformation, σ^{Af}		100
Young's modulus, *E*		$5{,}27 \cdot 10^4$
Poisson's ratio		0,36
Density	*g/cm³*	6,45

To investigate the damping properties of the shape memory alloy, the energy of the elastic strain of the forward and inverse phase transformations according to the formula (1) was determined. The energy of the elastic strain W_{elast} is found as the difference of areas under the loading and unloading curves (Fig. 2) [12].

$$U = \frac{1}{2}\frac{\sigma^2}{E}, \tag{1}$$

where σ – stress; E –Young's modulus.

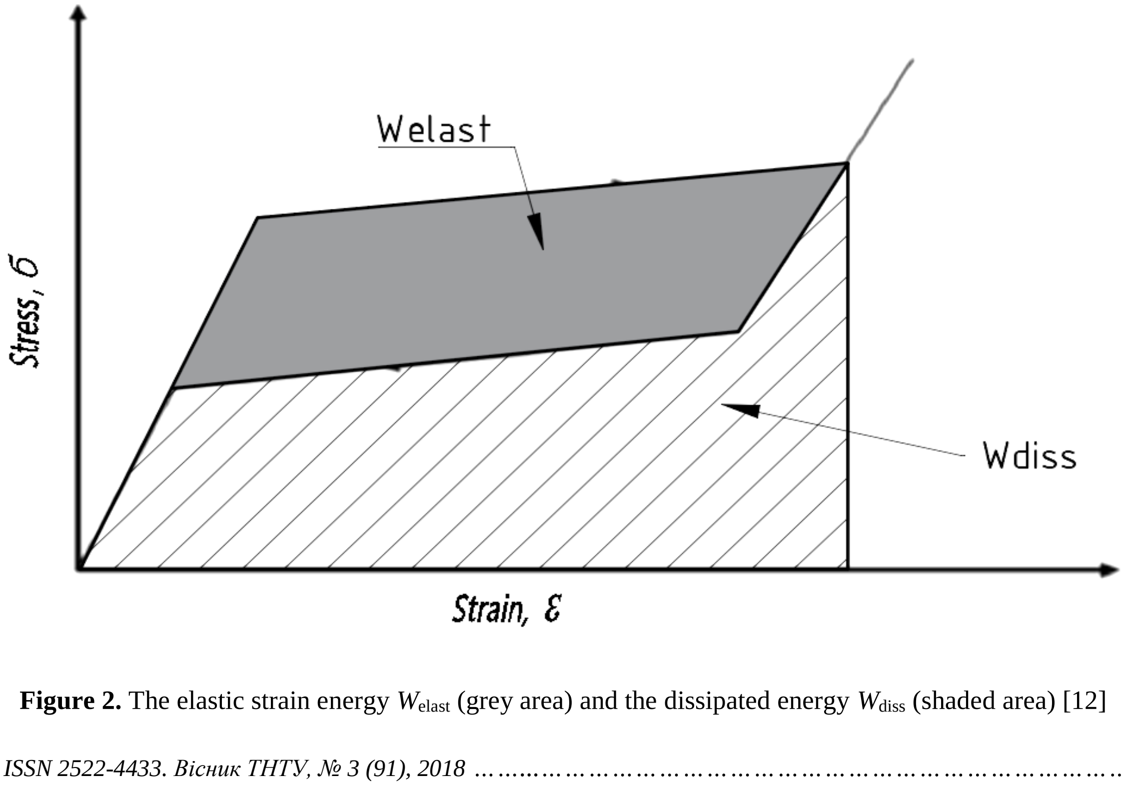

Figure 2. The elastic strain energy W_{elast} (grey area) and the dissipated energy W_{diss} (shaded area) [12]

Mechanical behaviour of the shape memory alloy (the effect of pseudoelasticity) was simulated using the finite elements method using the applied software package ANSYS Workbench 17,1 under static [13] and repeating static [14] tensile strain and unloading, using the experimentally obtained characteristics of the mechanical properties [11]. The finite elements model of the nickel-titanium alloy wire of diameter $d = 1{,}5\ mm$ and length $L = 30\ mm$ is fastened rigidly in the point *A* and loaded along the axis by the force *Z*, which is applied in the point *B* (Fig. 3). The model is discreted by the finite elements SOLID186. SOLID186. is the 3D element, composed of 20 nodes, every of which posses three levels of freedom: the nodes displacement towards the node *X*, *Y*, *Z*, possessing the property of elasticity, plasticity, hyperelasticity, creep, rigidity, sufficient bending and deformations. It is of mixed composition ability to simulate the elasto-plastic deformations and totally unpressed hyperelastic materials. The element can be loaded by the stresses, displacements and the temperature affects both separately and being combined [7]. General number of finite elements (FE) is 896, nodes – 4531. The size of one element FE is *0,5 mm*. The whole stage of simulation was in 13 steps with 100 sub-steps.

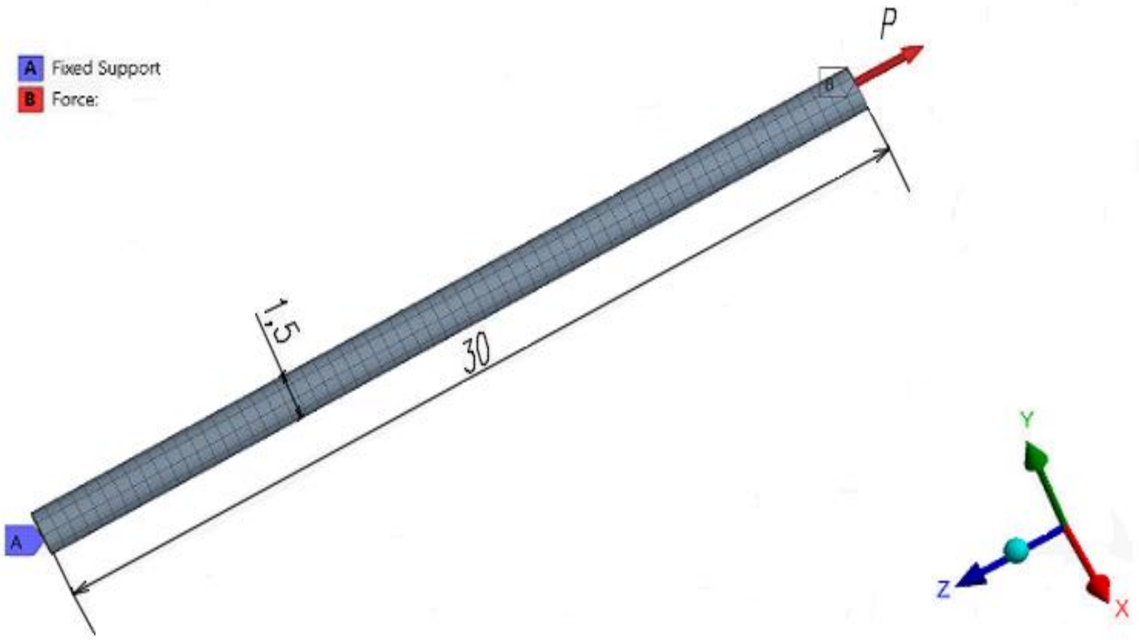

Figure 3. The finite element 3D model of wire

Analysis of results and discussions. The experimental data on cyclic deformation of nickel-titanium alloy, obtained under the variable amplitude of the tensile strain, are described in the papers [11, 14]. In Fig. 4 dependence of stresses on deformation under the variable amplitude of loading at constant loading rate *0,2 mm/sec* till the total fracture of the specimen is presented.

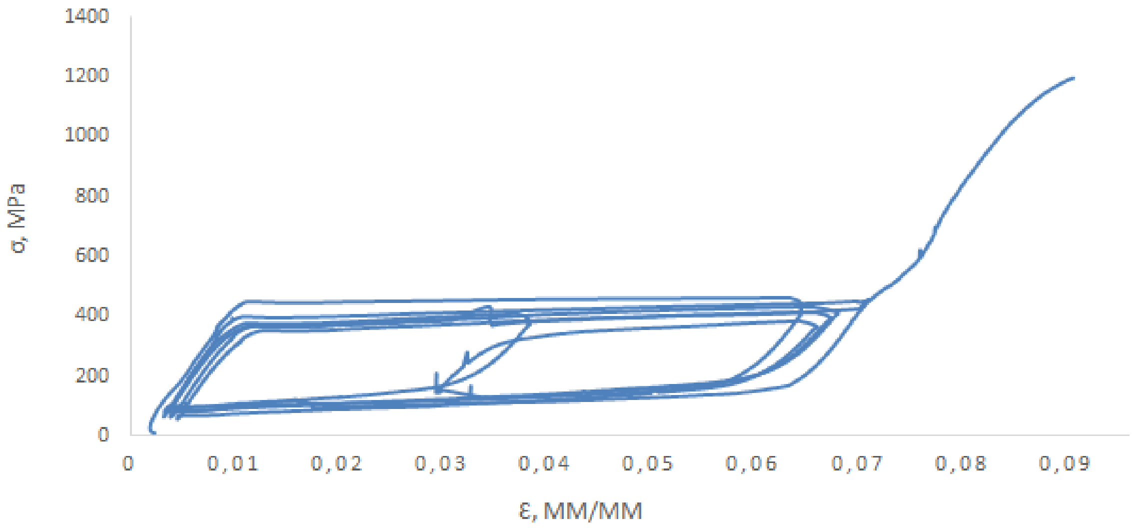

Figure 4. Cyclic deformation curve of nickel-titanium alloy. Displacement rate of the bar is *0,2 mm/s*

On Table 2 experimental and numerical results of maximum and minimum stresses, as well as strains at every cycle of loading and unloading, resulted from the applied force, are presented. The results of experiments are well agreed with the modelling results. The maximum error of stresses at all loading cycles is 10,1% and strains – 6,1%.

Table 2

Maximum and minimum stresses and strains at each cycle (loading and unloading)

Cycle №	Force, N	*ε, mm/mm*		Error, %	*σ, MPa*		Error, %
		Exp.	Model		Exp.	Model	
I	817	0,063	0,065	3,1	462	481	4,1
	130	0,003	0,001	–	76	82	7,8
II	800	0,071	0,070	1,4	456	494	8,3
	170	0,003	0,001	–	96	89	7,2
III	710	0,037	0,038	2,7	410	444	8,2
	120	0,003	0,001	–	97	90	7,2
IV	763	0,065	0,069	6,1	432	475	9,9
	140	0,003	0,001	–	79	85	10,1
V	730	0,065	0,068	4,6	413	455	10,1
	240	0,035	0,032	8,5	128	129	0,7
VI	660	0,065	0,066	1,5	376	411	9,3
	100	0,004	0,001	–	60	59	1,1
VII	2100	0,090	0,087	3,3	1200	1240	3,7

The obtained results stresses dependence on strains, being numerically simulated, are compared with the experimental results.

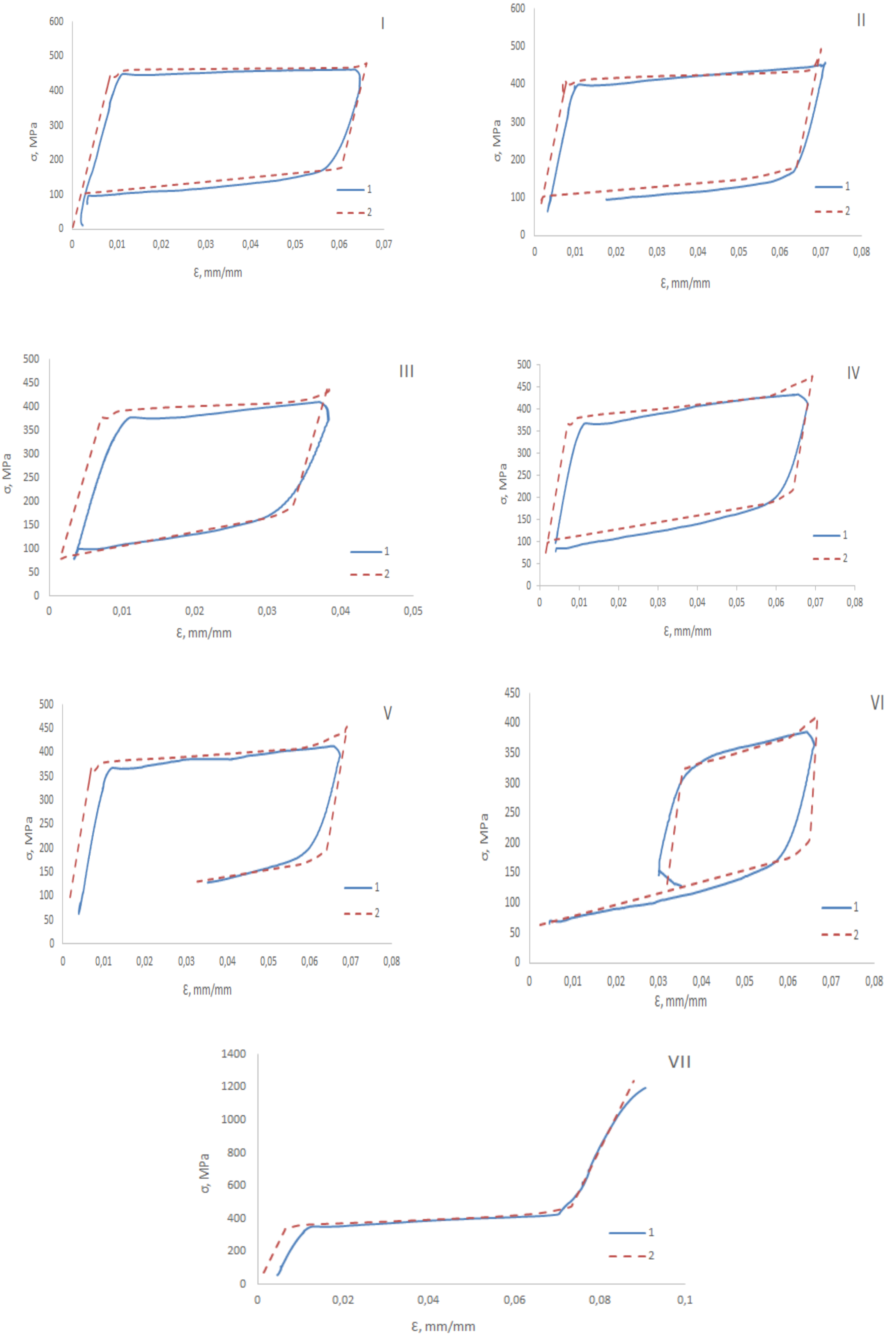

Figure 5. Stress-strain dependencies obtained from, 1 – experiment; 2 – modelling. I – VII – numbers of cycle (loading and unloading) according to Table 2

The energy of the elastic deformation, obtained experimentally and while modeling, is presented on Table 3, where U^{Ms} – elastic energy of the martensite phase transformations start and finish; U^{Mf} – the martensite phase transformations finish; U^{As} – the austenite phase transformations start and finish; U^{Af} – the austenite phase transformations finish.

Table 3

Values of deformation energy in the points of forward and phase transformations (*kJ*)

Cycle №	U^{Ms}, kJ		U^{Mf}, kJ		U^{As}, kJ		U^{Af}, kJ	
	Exp.	Model	Exp.	Model	Exp.	Model	Exp.	Model
I	192	199	200	219	31,4	30,1	8,92	7,18
II	149	151	197	231	27,4	31,1	8,74	7,51
III	134	134	159	187	31,7	30,1	8,20	6,78
IV	127	132	177	214	40,2	41,2	6,85	8,38

On Table 4 the experimental and numerical values of the elastic deformation energy and dissipated energy at very loading cycle are presented, where W_{elast} – the square of all area of the elastic energy of deformation; W_{diss} – the square of all area of dissipated energy.

Table 4

The elastic strain and dissipated energy

Cycle №	W_{elast}, kJ		Error, %	W_{diss}, kJ		Error, %
	Exp.	Model		Exp.	Model	
I	268	287	6,9	22,2	24,6	10,8
II	226	245	8,3	23,0	22,4	2,6
III	191	208	9,1	19,8	22,7	10
IV	189	210	1,9	29,1	26,9	7,2

The maximum error of finding the energy of elastic deformation W_{elast} is 10,9% and the dissipated energy at all loading cycles does not exceed 10,8%.

Conclusions. Taking advantage of the finite elements method the pseudoelastic behaviour of the Ni-Ti alloy under the variable amplitude of loading has been modelled. The results of numerical 3D modelling of the pseudoelastic behaviour are well agreed with the experimental curves of cyclic strain of the Ni-Ti alloy wire. The maximum error of stresses at all loading cycles is 10,1% and the stretch deformation is 6,1%. The numerical and experimental values of the dissipated energy and the energy of elastic deformation of the nickel-titanium alloy, resulted from the applied force, under variable loading amplitudes, the maximum error between which does not exceed 10,9%, have been obtained.

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УДК 539.3

МОДЕЛЮВАННЯ МЕТОДОМ СКІНЧЕНИХ ЕЛЕМЕНТІВ МЕХАНІЧНОЇ ПОВЕДІНКИ СПЛАВІВ З ПАМ’ЯТТЮ ФОРМИ

Петро Ясній; Олександр Дивдик; Надія Луцик; Володимир Ясній

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Методом скінчених елементів змодельовано й експериментально досліджено псевдопружну поведінку нікель-титанового сплаву за змінної амплітуди навантаження. Зразки з нікель-титанового сплаву (Ni – 55,8%, Ti – 44,2%) діаметром d = 1,5 мм і довжиною робочої ділянки L = 30 мм досліджували за одновісного розтягу на випробувальній машині FP-100 при кімнатній температурі на повітрі. Експериментально визначено механічні характеристики матеріалу та напруження старту й фінішу прямих і зворотних фазових перетворень, використаних при моделюванні. Створено скінченоелементну тривимірну модель, здатну відтворювати псевдопружну поведінку за статичного й повторно-статичного навантаження розтягом та розвантаження. За результатами моделювання методом скінчених елементів у середовищі ПК ANSYS Workbench 17.1 отримано залежності напружень від деформації в кожному циклі за змінної амплітуди навантаження. Виявлено, що за змінної амплітуди навантаження напруження початку та закінчення прямих і зворотних фазових перетворень змінюються у кожному циклі, а розрахункові залежності напружень від деформацій задовільно узгоджуються з експериментальними. Похибка напружень, обчислених методом скінчених елементів упродовж усіх циклів навантаження не перевищує 10,1%, а деформацій – 6,1%. У точках, які відповідають напруженням прямих і зворотних перетворень, обчислена енергія пружної деформації та енергія дисипації. Похибка енергії пружної деформації при чисельному моделюванні не перевищує 10,9%, а енергії розсіювання (дисипації) – 10,8% порівняно з експериментальними даними. Отримані результати мають теоретичне й прикладне значення для моделювання псевдопружної поведінки, міцності й витривалості конструкцій з сплавів з пам’яттю форми за сталої та змінної амплітуди навантаження.*

Ключові слова: *сплав з пам’яттю форми, псевдопружність, напруження фазових перетворень, мартенсит, аустеніт, енергія дисипації.*

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