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To the relation between the orientation of the pore channels and the mechanical properties of porous NiTi shape memory alloy

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The deformation behavior of porous shape memory alloy (SMA) is determined both by the features of their inhomogeneous structure and the martensitic transformation. The present work shows the results of simulation aimed at clarifying the influence of these factors on the behavior of porous SMA. The structures of porous samples with different orientations of the pore channels are approximated by sets of beams of various configurations, and the constitutive relations of the microstructural model are used for calculations of the strain associated with martensitic transformations. The calculations are performed for a dense SMA sample, porous SMA samples with longitudinal and transverse orientation of the pore channels and similar porous samples that do not undergo martensitic transitions. Simulations of isothermal compression at different temperatures and strain variations at cooling and heating under a constant stress are carried out. It is shown that the reorientation of martensite in a dense SMA specimen begins at a higher stress than in porous specimens. Moreover, a dense sample has a higher yield stress in both austenitic and martensitic states. At the same stress level, a porous SMA sample with transverse pore channels accumulates a larger strain than a sample with longitudinal channels. The same relation is observed for similar samples of an alloy without transformations. Porous SMA accumulates greater strain in comparison with common porous metal due to the reorientation of martensite and pseudoelasticity. The largest strain accumulated on cooling under a constant stress among the samples under consideration occurs in a porous sample with transverse pore channels.

Keywords: modeling, shape memory alloys, porous NiTi.

УДК: 538.91

О связи ориентации поровых каналов с механическими свойствами пористого сплава с памятью формы NiTi

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Деформационное поведение пористых сплавов с памятью формы (СПФ) определяется как особенностями их неоднородной структуры, так и мартенситным превращением. В настоящей работе показаны результаты моделирования, направленные на изучение влияния этих факторов на особенности поведения пористого СПФ. Структуры пористых образцов с разной ориентацией поровых каналов аппроксимированы наборами балок различных конфигураций, а деформацию СПФ, связанную с мартенситными переходами, рассчитывали в рамках макроструктурной модели. Расчеты выполнены для сплошного образца из СПФ, пористых образцов из СПФ с различной ориентацией поровых каналов и таких же пористых образцов, не испытывающих мартенситных переходов. Выполнено моделирование изотермического сжатия образцов при различных температурах, а также их охлаждения и нагрева под постоянным напряжением. Показано, что при сжатии сплошного образца из СПФ, находящегося в мартенситном состоянии, переориентация мартенсита в нем начинается при больших напряжениях, чем в пористых образцах. К тому же, сплошные образцы демонстрируют значительно более высокие значения пределов текучести как в аустенитном, так и в мартенситном состоянии. При одном уровне напряжений пористые образцы из СПФ и из сплава, не испытывающего фазового превращения, с поперечно ориентированными поровыми каналами накапливают большую деформацию, чем образцы с продольной ориентацией поровых каналов. Пористые СПФ накапливают большую деформацию, чем пористые образцы без мартенситных переходов, которая связана с переориентацией мартенсита и псевдоупругостью. Среди рассматриваемых образцов наибольшее значение накопленной при охлаждении под постоянным напряжением деформации наблюдается у пористого СПФ с поперечно ориентированными поровыми каналами.

Ключевые слова: моделирование, сплавы с памятью формы, пористый NiTi.

1. Introduction

Porous NiTi-based shape alloys (SMA) have been known for more than two decades, when they began to be produced due to the prospect of their usage as materials for bone implants, and since then, research on their structure and properties has commenced [1,2]. The mechanical properties of porous SMA are determined by the heterogeneous structure of the material and martensitic phase transformations. Thus, modeling the deformation of such specimens must account for both of these factors, which are the cause of low effective strain-hardening coefficient and the similarity of stress-strain diagrams to those of human bones [3,4]. This is important for the development of technological applications using porous SMA as materials for vibration damping and for medical bone implants. There is a large number of works devoted to experimental investigation of porous NiTi obtained by various methods of powder metallurgy and additive manufacturing, which can be found in the review [5]. The production methods and their technological parameters highly influence the structure and properties of the samples. For instance, in the work by M. Kaya et al. [6] NiTi samples obtained by self-propagating high-temperature synthesis (SHS) had pores aligned along or normal to the sample axis, forming a longitudinal or transverse pore structure depending on the combustion wave propagation direction. The mechanical properties of these two types of samples differed from each other and from the dense SMA of the same composition. The explanation of this difference is an actual issue, which can hardly be obtained by just analyzing experimental data. In work [7], the authors supposed that the differences in the mechanical properties of porous SMA are due to the differences in stresses in the inter-pore ligaments. An attempt to deal with this problem by means of modeling based on the approximation of a porous material as a beam structure is presented in this work.

2. Modeling

There are different approaches to modeling of the behavior of porous SMA [8–12]. However, most of them do not allow taking into account peculiarities of the structure of SMA with high porosity. At the same time, the relationship between the pore structure and the deformation behavior can be studied on the samples with different orientations of the pore channels.

Fig. 1a, c illustrate the structures of porous NiTi samples with longitudinal (parallel to the specimen axis) [13] and transverse (perpendicular to the specimen axis) [14] orientations of the pore channels. In the previous work [15], it was suggested that samples with longitudinal pore channels can be considered as a set of cascades of curved beams (Fig. 1b), each of them characterized by a radius, central angle and cross-section dimensions. In another work [16], samples with transversally oriented pore channels were represented by flat slotted springs (Fig. 1d), characterized by the length and the cross-section parameters of horizontal beams. To avoid solving a complicated boundary-value problem, the stress and displacements in the beams were calculated within the following hypotheses: (1) the deformation of the beam is such as if it were loaded by a uniform moment equal to that in its mostly strained region; and (2) the Bernoulli plane-sections hypothesis, according to which any beam is shaped as a circular arc during all the deformation process. The mean strain was calculated as the ratio of the sum of the displacements produced by all structural elements to the height of the samples.

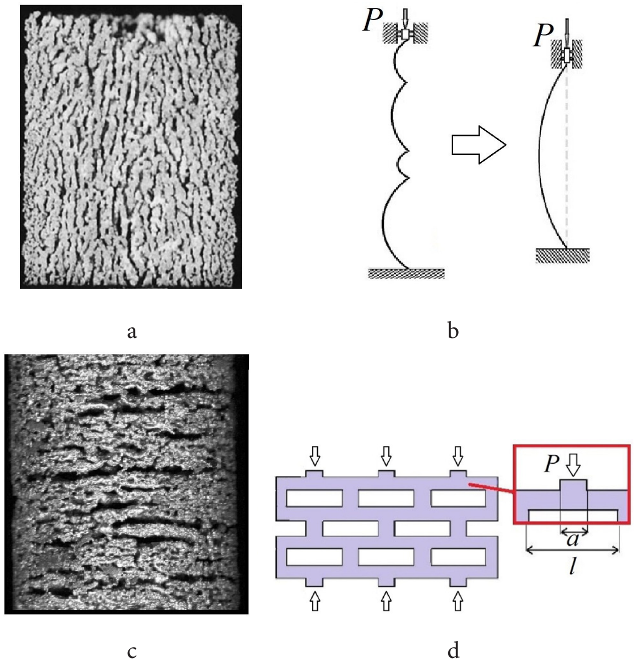

Fig. 1. Porous NiTi samples obtained by SHS and corresponding beam structures used for their approximation: porous NiTi sample with longitudinal pore channels [13] (a), a cascade of curved beams (b); sample with transverse pore channels [14] (c), a flat slotted spring (d).

An important step in modeling of the behavior of porous SMA is the selection of constitutive relations for calculating the inelastic strain of the SMA. There are various phenomenological and microstructural models for simulation of SMA behavior [17–20]. In this work, the microstructural model [21] is used. It has proven its efficiency in simulation of functional and mechanical properties of SMA. The constitutive relations of this model consider the hierarchy of structural levels and deformation mechanisms in SMA: elasticity, forward and reverse martensitic transformations, martensite reorientation and dislocation plasticity.

To study the influence of various inelastic deformation mechanisms on the behavior of porous SMA three types of samples are considered: a dense SMA, a porous SMA and porous samples experiencing only dislocation plastic deformation. Each type of SMA porous structures is characterized by geometrical parameters taken from analyses of microphotographs. For porous samples without phase transformation, these parameters are assumed to be the same as those of the porous SMA. The obtained results allow establishing relations between the features of the deformation behavior and the structure of the porous SMA sample.

First, the models of porous SMA and its constants are verified by simulating the deformation of porous NiTi samples with a porosity of 54%, the same as in the experimental work 6]. To calculate the behavior of SMA samples, the following constant values are used: transformation temperatures $M_s = 47°C$, $M_f = 65°C$, $A_s = 84°C$, $A_f = 102°C$, latent heat $q_0 = -160$ MJ/m^3, Young's modulus of austenite is equal to 70 GPa and 30 GPa for martensite; Poisson's ratio is equal to 0.33 for both phases.

The stress-strain curves of isothermal uniaxial compression of porous samples in the martensitic state with longitudinal and transverse orientations of the pore channels are shown in Fig. 2.

The non-smoothness in the calculated stress-strain curves is associated with the non-simultaneous start of various deformation mechanisms in the beams with different geometric parameters, and thus their different contributions to the total strain. Fig. 2 illustrates that a porous SMA sample a transverse orientation of the pore channels accumulates at a given stress a larger strain than the strain of a sample with a longitudinal structure. There is an agreement between the theoretical and the experimental data.

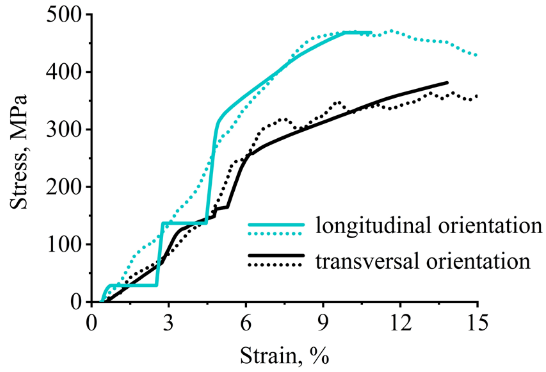

Fig. 2. (Color online) Compression stress-strain curves of porous NiTi in the martensitic state: numerical results (solid lines) and experimental data (dot lines) [6].

3. Results

Simulation of axial isothermal compression is made for the three types of objects: a dense SMA sample, a porous SMA sample, and a porous sample without martensitic transformation. The longitudinal and transverse orientations of the pore channels are considered. Samples are "deformed" at room temperature, when the SMA is in the martensitic state, and at a high temperature, when it is in the austenitic state.

On the stress-strain curves of both porous and dense SMA, one can see the stage of the elastic strain follows by the accumulation of inelastic strain (Fig. 3). For SMA samples deformed in the martensitic state, this inelastic strain is due to the reorientation of martensite. The accumulation of inelastic strain in austenite is due to the stress induced martensitic transformation — the effect of pseudoelasticity (Fig. 3b). The dense sample exhibits significantly higher values of the yield stress in both the austenitic and martensitic states compared to porous samples with transverse oriented pore channels. Comparison of the deformation of different porous samples leads to a conclusion that the value of the inelastic strain depends on the prevailing orientation of pores distribution. At the same stress level, porous samples with the transverse orientation of the pore channels accumulate significantly greater strain than samples with longitudinally oriented pores.

In Fig. 4, numerical results for uniaxial compression of porous specimens with the same pore structures made of SMA and of a metal with the same characteristics of elasticity and plasticity but without martensitic transformation are compared. Inelastic strain in SMA samples in the martensitic state is due to the martensite reorientation; therefore, it is much higher than the strain in a common porous metal, in which the dislocation plastic slip is the only mechanism of inelastic deformation (Fig. 4a). After deformation in the austenitic state (Fig. 4b), porous SMA samples on unloading demonstrate pseudoelastic strain recovery, and thus they partially retain the functional behavior of a dense SMA. Unloading of a common porous metal is elastic.

From the results shown in Fig. 4, one can also conclude that at the same stress level the samples with transversally oriented pore channels accumulate greater strain both for porous SMA and for porous alloys without martensitic transformations.

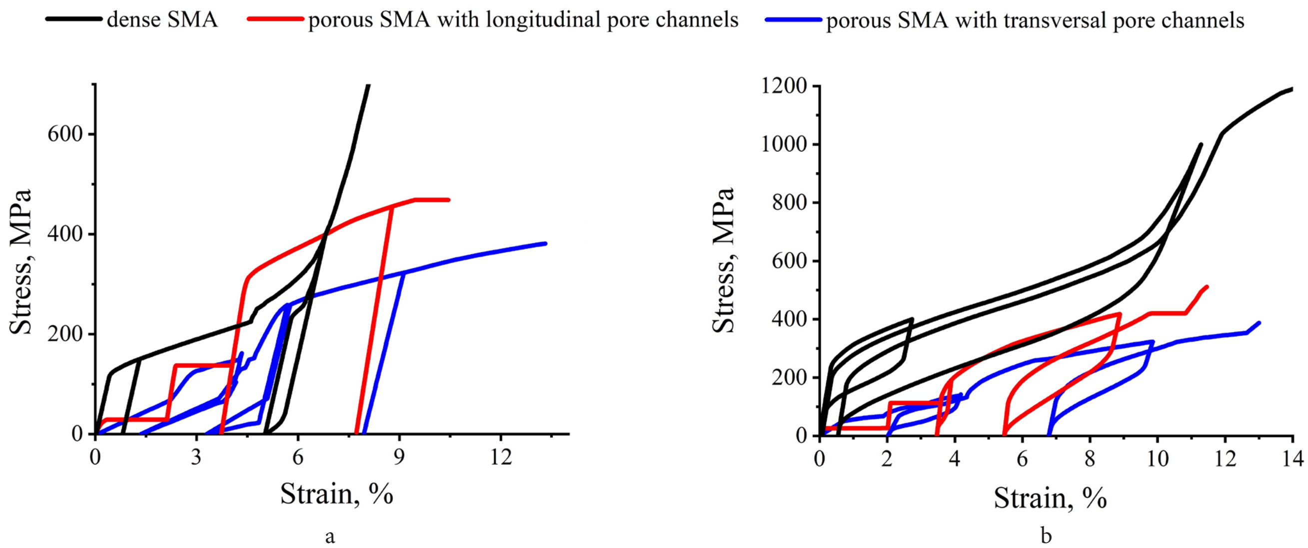

Fig. 3. (Color online) Calculated stress — strain diagrams for the specimens under compression in martensitic (a) and austenitic (b) state.

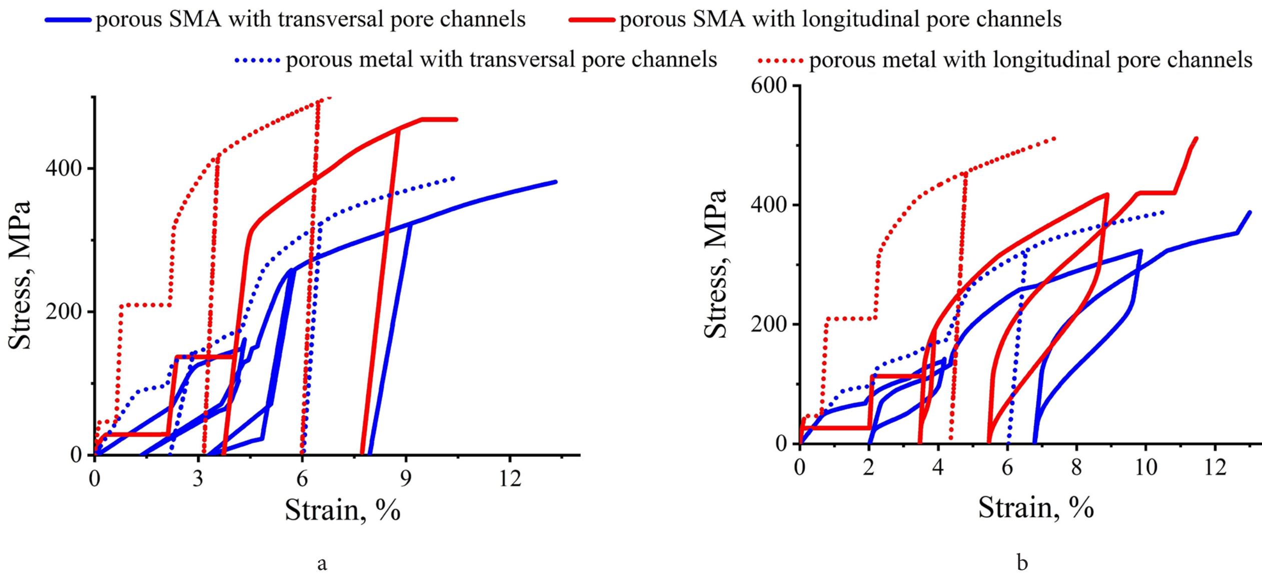

Fig. 4. (Color online) Simulation of uniaxial compression with intermediate unloadings for the specimens under compression in the martensitic (a) and austenitic (b) state.

To clarify the differences in the functional properties of samples with different orientations of pore channels, the strain variation is simulated for samples pre-loaded in the austenitic state to a stress of 100 MPa (Fig. 5) and subjected to cooling and heating under a constant stress.

From this figure, one can see that the shape memory effect is much greater for a porous sample with transversally oriented pore channels.

4. Conclusion

The functional properties of porous SMA are determined by both the phase transformations and the features of the pore structure. For porous SMA specimens both in the martensitic and the austenitic states as well as for the same porous samples without martensitic transformations, the strain associated with the isothermal loading up to a given stress is greater for samples with transverse orientation of the pore channels than that for the samples with longitudinal pore channels. The same relation holds for the strains accumulated in porous SMA samples on cooling and heating under a constant stress.

A porous SMA partially retains the functional behavior of a dense SMA demonstrating shape memory effect on heating, pseudoelasticity at deformation in the austenitic state and martensite reorientation at deformation in the martensitic state.

Since the stress needed to cause the martensite reorientation or the appearance of the stress-induced martensite is less than the dislocation plasticity yield limit, porous SMA samples when loaded to a given value of the stress acquire a much larger strain than porous samples made of the same material but without martensitic transformations.

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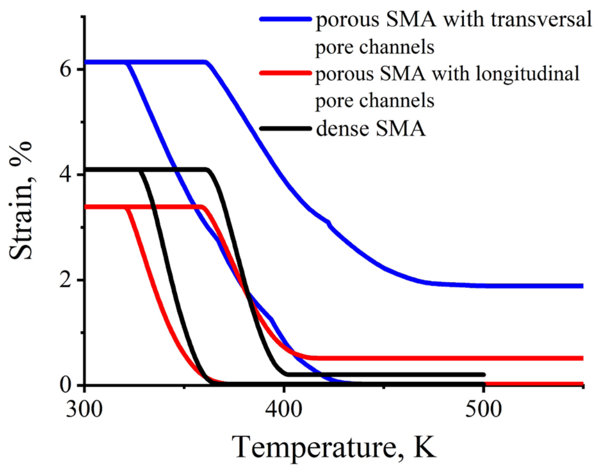

Fig. 5. (Color online) Modeling of the shape memory effect during cooling and heating of porous SMA samples with different orientations of pore channels and dense SMA under a constant stress of 100 MPa.

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