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SIMULATION OF BEHAVIOR OF FUNCTIONALLY - HETEROGENEOUS MATERIALS UNDER TEMPERATURE LOADS

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The paper considers the issue of nonlinear mathematical modeling of functionally inhomogeneous materials at temperature loads. The proposed model makes it possible to describe the thermo-pseudo-plastic behavior of the material at the point. The diagram of pseudo-elastic material consisting of three curvilinear sections is used. This approach leads to an unstable stress-strain diagram, and to describe the thermo-mechanical behavior of samples of different shapes, it is necessary to have a solution of the boundary value problem taking into account the development of the deformation front of the phase transformation. This takes into account not only the ambient temperature, but also the heat released at the point during the phase transition. A numerical procedure for calculating a material diagram has been developed, which is a curve enveloping a family of *material diagrams constructed for certain laws of change in the velocity of the deformation rupture front. An integrated diagram of the material under the influence of a complex load is constructed.*

Keywords: phenomenological model, nonlinear material model, materials with shape memory, thermo-pseudo-plasticity, numerical procedure for calculating the diagram.

Problem statement. Currently, a number of models are known to describe the thermo-mechanical behavior of functionally inhomogeneous materials, in particular shape memory alloys [3; 4;7]. Most of them are based on classical ideas, that is aim to directly describe the experimental data obtained on different macro samples under simple and complex loads. However, as established in experimental studies, the behavior of the material at the point of the body in the General case may be different from the behavior of the sample as a whole [5; 6].

The aim of the work is to form a nonlinear phenomenological model, which describes the properties of alloys with shape memory and thermo-pseudo-plastic behavior of the material at the point.

Solving the problem.

To describe the elastic deformation and the deformation of the phase transformation, we use a diagram of a pseudo-elastic material consisting of three curvilinear sections. This interpretation leads to an unstable stress-strain diagram, and to describe the thermo mechanical behavior of samples of different shapes, it is necessary to have a solution of the boundary value problem taking into account the development of the phase transformation deformation front.

In this case, we will take into account not only the ambient temperature, but also the heat released at the point during the phase transition. This interpretation allowed us to formulate a nonlinear phenomenological model from a single position and to describe a number of experimental data on different samples under different loading conditions, including cyclic temperature and force effects. Specific dependences for mechanical parameters are established. It is shown that the phase separation boundary moves at a constant speed for the selected temperature. It is confirmed that classical material diagrams are a curve that encircles a family of material diagrams at a point that is constructed for certain laws of change in the velocity of the deformation rupture front.

Generalized dependence between voltage σ and deformation ε, at the material point is modeled by the curve shown in Figure 1. When constructing such a diagram, points are set (σ_M,ε_M), (σ_m,ε_m) and functions $\varepsilon=\psi_i(\sigma)$, *i=1, 2, 3.*

Variable deformation of the phase transformation is defined as the difference:

$$\varepsilon_T=\psi_3(\sigma)-\psi_3(\sigma). \tag{1}$$

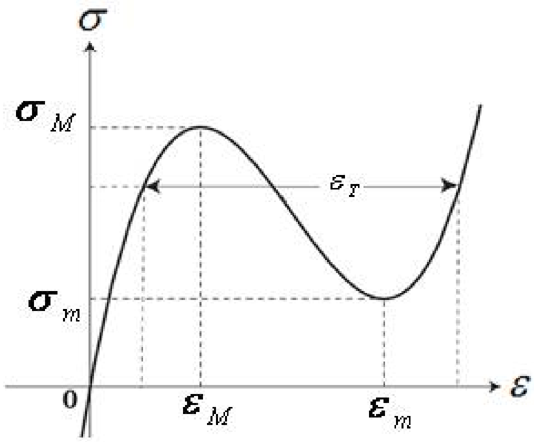

Figure 1. Stress-strain curve for two-phase material

Functions $\psi_i(\sigma)$ charts must meet the following requirements:

$$\begin{aligned}&\psi_1(0)=0,\psi_1(\sigma_M)=\varepsilon_M,\psi_1'(\sigma_M)>0,\\&\psi_2(\sigma_M)=\varepsilon_M,\psi_2(\sigma_m)=\varepsilon_m,\psi_2'(\sigma)<0,\\&\psi_3(\sigma_m)=\varepsilon_m,\ \psi_3'(\sigma)>0.\end{aligned} \quad (2)$$

The field of displacements in the sample must be continuous:

$$u(x)=\begin{cases}\psi_3(\sigma)x, 0\le x<s,\\ \psi_1(\sigma)x+\varepsilon_T, s\le x<L.\end{cases}$$

The corresponding piecewise inhomogeneous distribution of deformation in the shear is given by the formula [1; 4]:

$$\varepsilon(x)=\begin{cases}\psi_3(\sigma), 0\le x<s,\\ \psi_1(\sigma), s\le x<L.\end{cases}$$

The relationship between increasing length $u(L)=\delta$ shear and stress is determined by the expression:

$$\delta=\psi_3(\sigma)s+\psi_1(\sigma)(L-s). \quad (3)$$

Where *s* denotes the phase boundary.

In general, equation (3) makes it possible to determine the family $\delta(\sigma,s)$. If *δ* is given, then we can find the stress by solving the boundary value problem of nonlinear elasticity in accordance with conditions (2). In this case, from expression (3) it is not possible to immediately determine how much the position of the phase boundary is unknown. To unambiguously solve this problem, it is necessary to have auxiliary information in addition to equation (2-3), physical relations $\varepsilon=\psi_i(\sigma)$, *i=1, 2, 3,* boundary conditions and requirements for smoothness. These equations are sufficient in the absence of unstable sections of the diagram for ordinary elastic materials for which the stress increases monotonically with increasing strain.

Violation of uniqueness occurs in (3), if specified σ, but not δ. In this case, the problem is solved by introducing the concept of driving force *f*. It is defined as follows:

$$f(\sigma)=\int_{\sigma_0}^{\sigma}\varepsilon_T(\sigma)\,d\sigma. \quad (4)$$

Where $\sigma_0=(\sigma_M+\sigma_m)/2$ – Maxwell's tension. Since the voltage at equilibrium in the mixed phase must be between σ_m and σ_M, then the range of possible values of the driving force will be as follows $f\in[f_m,f_M]$.

Consider an auxiliary problem in which you need to define the functions of time $\sigma=\sigma(t),\ s=s(t),\ \delta=\delta(t)$.

The time derivative of the dependence (3) gives the following linear equation:

$$\dot{\delta}=\varepsilon_T\dot{s}+\left(\varepsilon_T'(\sigma)s+\psi_1'(\sigma)L\right)\dot{\sigma}. \quad (5)$$

Here the dot marks the time pass, and the dash the voltage derivative σ.

As a result of (5) in the General case, the tangent module of the sample diagram can be defined as follows:

$$\frac{d\sigma}{d\delta}=\frac{1-\varepsilon_T(\sigma)\dot{s}/\dot{\delta}}{\psi_1'(\sigma)L+\varepsilon_T'(\sigma)s}.$$

When calculating it is necessary to pre-define the functions $\sigma=\sigma(t)$, $s=s(t)$. To solve this problem, we need to add the kinetic response function to equation (5) $\dot{s}=\Phi(f)$ and the expression for the driving force (4), which can be represented as follows:

$$f(\sigma)=\int_{\sigma_0}^{\sigma}\left[\psi_3(\sigma)-\psi_1(\sigma)\right]d\sigma. \quad (6)$$

For three-link two-phase material with variable modulus of elasticity and correspondingly variable transformation deformation ε_T On the basis of the above formulas (5) and (6), it is possible to write the dependences between the stress and the increase in the length of the elastic sample, as well as for the driving force.

The equation of the first section of the diagram for $\varepsilon\in[0;\varepsilon_M],\ \sigma\in[0;\sigma_M]$, has the form:

$$\varepsilon(\sigma)=\psi_1(\sigma). \qquad (7)$$

Equation of the diagram on the plot $\varepsilon \in [\varepsilon_m;\infty)$, $\sigma \in [\sigma_m;\infty)$, has the form:

$$\varepsilon(\sigma)=\psi_3(\sigma).$$

Note that the time of the process in the second section $\varepsilon(\sigma)=\psi_2(\sigma)$. Much smaller compared to the course of deformation in the first and third sections. Therefore, we will assume that the phase transformation proceeds instantly.

In mechanics problems, where the behavior of materials in which phase transitions take place is studied, in order to construct the physical relations between stress and strain, it is necessary to additionally know the position in the sample of the phase transition front. $s=s(t)$ and the kinetic response function $\dot{s}=\Phi(f)$.

Conclusions: It is experimentally established that the behavior of the material at a point in the body in the General case differs from the behavior of the sample as a whole. The paper formulates a nonlinear phenomenological model to describe the properties of the material at the point. A diagram of a pseudoelastic material consisting of three nonlinear sections was used to describe the elastic deformation and the deformation of the phase transformation. This interpretation of the theory leads to an unstable stress-strain diagram and requires a solution of the boundary value problem taking into account the development of the transformation deformation front. This allowed from the standpoint of the proposed nonlinear model of the material to describe a number of experimental data on different samples under different loading conditions.

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