THERMOMECHANICAL CYCLES IN MARTENSITE ENERGY CONVERTERS

T. A. Buldakova, Yu. V. Voitenko,
V. A. Likhachev, and A. I. Razov

UDC 621.499.669.018.2

We have studied the quantitative relationships governing the formation of thermomechanical cycles in heat engines with operational elements fabricated out of materials exhibiting the shape memory effect. With this purpose in mind, we have conducted experiments for two of the most common regimes under which materials function, namely: with a rigidly fixed amplitude of strain deformation, and for a scheme involving interconnected elements. We have plotted numerous phase diagrams in stress–strain–temperature coordinates and we have optimized such cycles in terms of their energy parameters. It has been established that the capacity of a metal to transform heat into mechanical work depends substantially on the form of the phase diagram, and this is at its maximum for sign-variable symmetric limit cycles. We undertook a theoretical calculation (and achieved positive results) of phase diagrams involving the application of structural-analytic theory insofar as this pertains to the functional properties of materials exhibiting the shape memory effect.

INTRODUCTION

Considerable attention is currently being devoted to the study of materials exhibiting the shape memory effect (SME) [1]. This is associated with their unique physicomechanical properties, in particular their ability to transform thermal energy into mechanical work. The simplest of converters are described in [2-10]. In a heat machine operating on a material exhibiting the state memory effect the thermomechanical cycle to produce useful work usually involves the following: in the preparatory stage the material is deformed along a channel of martensitic inelasticity, generating the appropriate expenditures of energy. In the next step, the acquired deforming strain is restored under conditions of reactive external forces and this, naturally, is accompanied by the performance of useful work. Given the appropriate choice of thermomechanical cycle, the general work balance may prove to be positive. Since martensitic inelasticity is entirely reversible, the useful work performed by the engine, on the whole, is all the greater, the greater the difference between the level of stresses generating martensitic inelasticity and the level of stresses in opposition to which the strain recovery takes place. All of this indicates that the efficiency of energy conversion must depend on the strain-force and temperature regimes under which the material functions, and it is, obviously, easy to raise this level through proper selection. However, specific means of optimizing the thermomechanical cycles of the heat engine employing the SME properties remain unclear. Experimental studies undertaken in [2-10] allow us only to estimate the approximate level of material energy efficiency or even to establish, if nothing else, the possibility of achieving useful work. In addition, only the very simplest of thermomechanical cycles were studied in [2-10].

In the present communication an attempt is made to optimize the limit thermomechanical cycles of a heat engine made of a material with shape memory in a regime in which adiabatic phenomena have been excluded. We will subsequently, following [7, 9], agree to refer to energy converters utilizing the properties of martensitic inelasticity as martensite energy converters (martensite engines, martensite drives, etc.).

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

We used two titanium nickelide alloys as the object of our study, and these were approximately equiatomic in composition. Alloy I exhibited the following characteristic temperatures: $M_S = 360$ K, $M_E = 280$ K, $A_S = 340$ K, $A_E = 450$ K, and alloy II had the following characteristic temperatures: $M_S = 330$ K, $M_E = 290$ K, $A_S = 390$ K, $A_E = 480$ K. All of the experiments were conducted in a torsion regime on single-piece specimens with an operating length of 25 mm and a diameter of 4 mm, according to the method described in [11]. The specimens were subjected to temperature,

Leningrad State University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 59, No. 2, pp. 269-277, August, 1990. Original article submitted March 27, 1989.

0022-0841/90/5902-1029$12.50

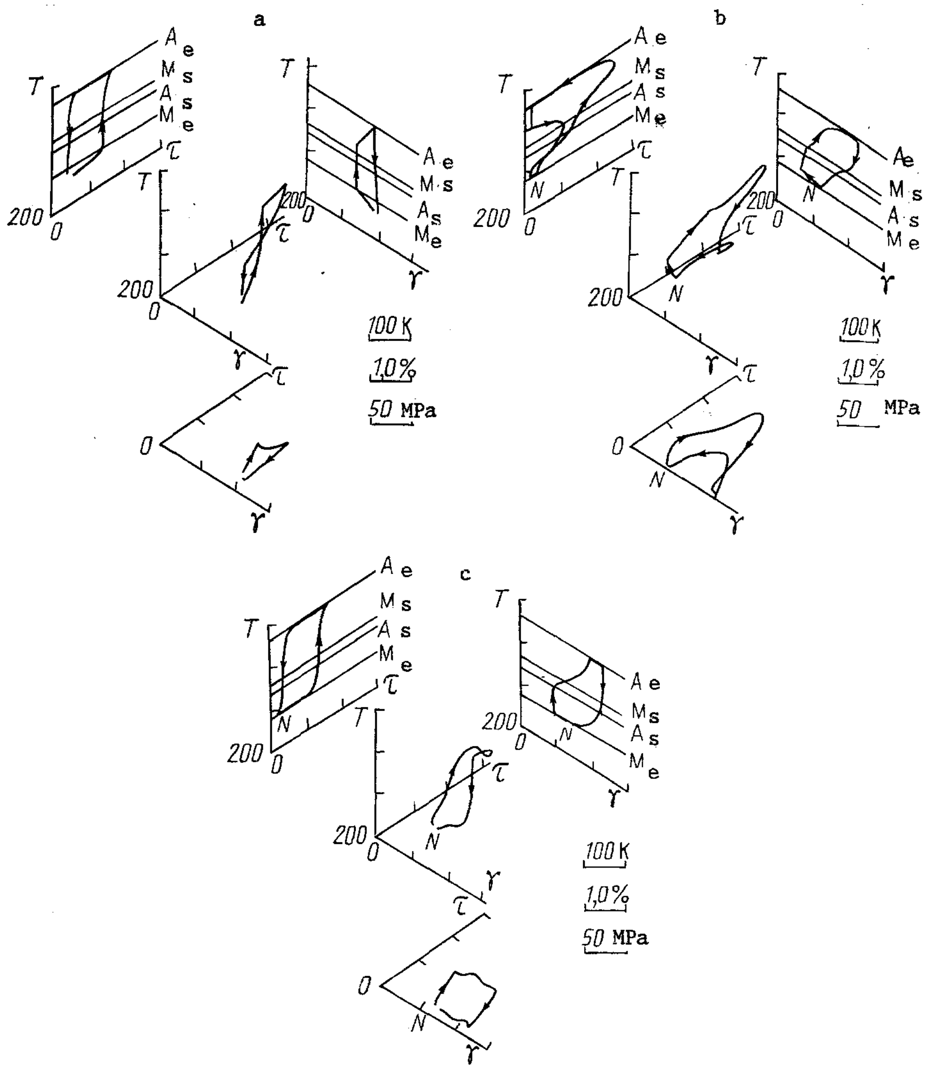

Fig. 1. Phase portraits of martensite engines with a nonfixed strain law. Alloy I.

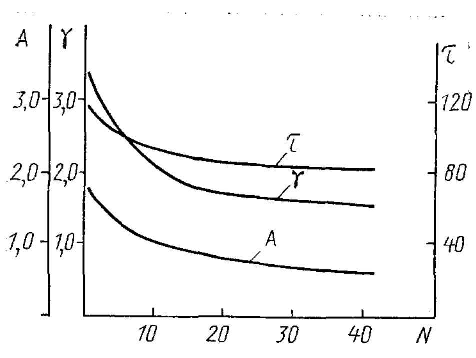

Fig. 2. Effect of the number of cycles of completed work on the maximum stress τ, the maximum scope of the strain γ, and work A within the operational cycle of energy converters operating as per the diagram (see Fig. 1). Alloy I. A, MJ/m^3; γ, T; τ, MPa.

force, and deformation effects in various combinations. As a result we produced three-dimensional diagrams in stress–strain temperature coordinates. Stress τ and strain γ were referred to the external filament of the operational section of the specimen, calculating the former on the basis of the measured torque in approximation of an ideally plastic body. We measured the temperature T with an accuracy of ±3 K. The control of the experiment, the recording of the measured parameters, and the processing of these data, were fully automated by means of a microcomputer. The experimental program made possible the realization of thermomechanical cycles close to those achieved in actual equipment of various designs. Optimization of the τ–γ–T diagrams on the basis of specified parameters was accomplished with a computer by solving a variational problem by the method of selecting from among various means for the synchronous variation in τ, γ, and T.

As was demonstrated by the experiments, regardless of the operating regime of the martensite energy converter (MEC) the τ–γ–T diagrams (MEC phase portraits) depend significantly on the number of completed work cycles. However, on completion of 20-50 cycles, the parameters assume constant steady values. It is precisely such limit cycles that will be discussed in the following.

A typical example of a titanium nickelide limit thermomechanical cycle is shown in Fig. 1a. Such a cycle is characteristic of martensite engines in which specified laws governing change in both strain and stress are absent (based on the classification from [8, 10], Scheme e. In practical terms, this scheme was achieved in a system of two sequentially connected specimens which were clamped at their outer ends in the test stand, as described in [10, 11]. During the experiment one of the specimens (the MEC working fluid) prior to insertion into the unit was subjected to torsional strain at a temperature M_E to a residual strain of $\gamma = 4.0\%$, followed by heat treatment from $M_E = 280$ K to $A_E = 450$ K. Another specimen (an auxiliary element) was not initially subjected to deformation, but rather subjected to the same heat cycles in counterphase. The working medium, as it is heated, restores the deformation, setting up torque in the system and turning the auxiliary elements. In the auxiliary-element heating stage the newly acquired deformation is restored, with the operational element twisted. The cycle is then repeated. In the strain restoration stages of the experiments and external moment of forces is applied to the boundary of specimen contact to counteract this restoration. This, and variation of the shapes of the temperature-curves made it possible to control the characteristics of the τ–γ–T diagrams.

As an example (see Fig. 1a) the useful work performed by the MEC and characterized by the surface area of the figure in τ–γ coordinates is comparatively small (0.16 MJ/m^3), the maximum stress values are also small (~100 MPa), and the reversible strains do not exceed 0.6%. However, even slight changes in the temperature regime brought about changes in the τ–γ–T diagrams. Two such diagrams are illustrated in Fig. 1b, c. Thus, in the example shown in Fig. 1b, in comparison to the example shown in Fig. 1a efficiency increased to 0.78 MJ/m^3, the maximum stresses rose to 125 MPa, and the magnitude of the reversible strain was equal to 1.6%. Analysis of the τ–γ–T diagrams permits us to draw the conclusion that optimization of the limit cycle is achieved through the most complete utilization of the channel of martensitic inelasticity with the lowest expenditures of energy on its realization and with the greatest scope of reversible strains.

An even greater increase in useful work within a single thermomechanical cycle can be achieved by raising the stresses while the level of reversed strains is maintained. However, as demonstrated experimentally, the increase in stresses in MEC such as those being examined here initiates a considerable nonclosure of the τ–γ–T cycle, accompanied by continuous attenuation of its characteristics (degradation of the limit cycle). An example of the impairment of the operational characteristics is seen in Fig. 2. One of the means of suppressing MEC degradation is the introduction of rigid limitations with respect to deformation in a regime of sign-variable loading. The subsequent figures illustrate the structure of the thermomechanical cycles, which we obtained in the sign-variable loading regime.

We achieved the sign-variable limit cycles in the following manner: A strain γ was imported to the working medium, altering it over time in approximation of harmonic law. Such an effect on the metal imitated the regime of operation for a uniformly rotating rotor-driven engine [7]. Synchronously with the deformation we changed the temperature of the working medium, attaining a maximum in material working efficiency. The reaction of the metal to effects of this kind was expressed by the corresponding generation and relaxation of reactive stresses. It turned out that the maximum operational efficiency of the material in the limit cycle might be attained if a number of requirements could be satisfied: 1) the thermomechanical cycle must not only be sign-variable with respect to stress, but it must be symmetrical as well; 2) the doubled strain amplitude must be close to 20%; 3) the heat-treatment cycles must be accomplished so that the maximum temperature be close to A_E, while the minimum temperature should be close to M_E; 4) the shape of the temperature-strain curves must be fully defined (it must be optimized). As an example of the limit cycle, optimized in terms of the above-cited variables, can be seen in Fig. 3a. In this cycle the efficiency amounts to 17 mJ/m^3, with the strain coverage equal to 20%, with the stresses changing from −270 to +270 MPa. The cycles in this case are completely closed, and the only parameter limiting the service life of the material is its fatigue. Impairment of the MEC properties on disruption

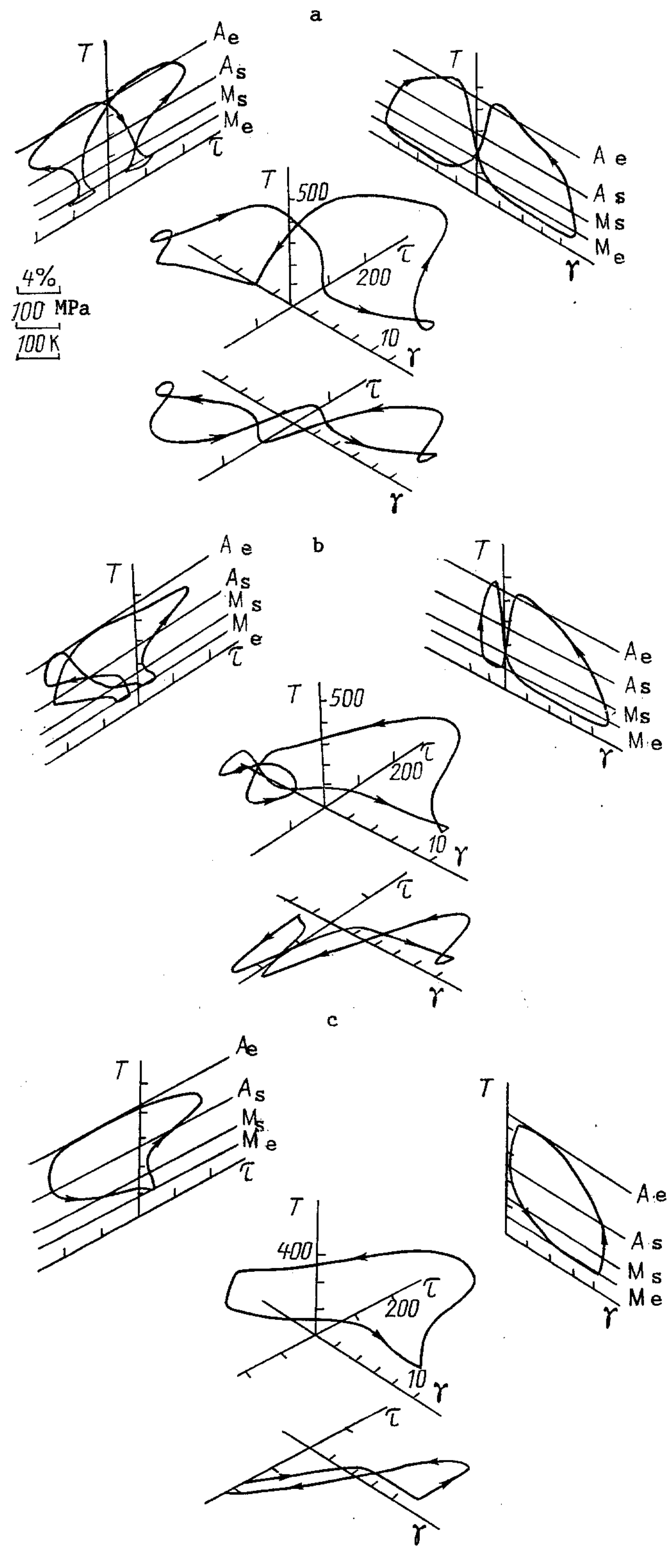

Fig. 3. Phase portraits of martensite engines with a fixed strain law. Alloy II.

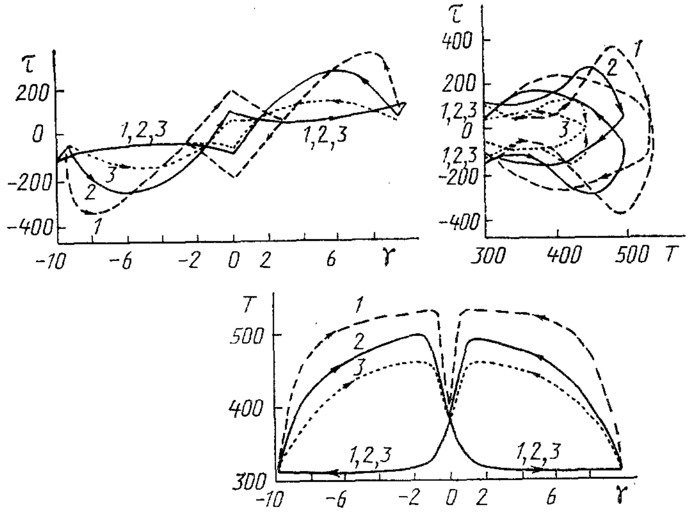

Fig. 4. Phase portrait of martensite engine operating in a regime with a fixed strain law for various T–γ diagrams. Alloy II.

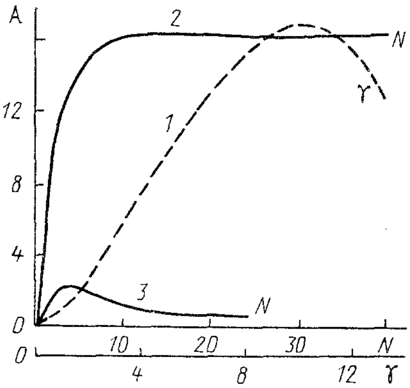

Fig. 5. Effect of the amplitude of strain γ (curve 1), the number of cycles in symmetric (curve 2) and nonsymmetric (curve 3) regimes on the operational efficiency of the MEC with a fixed strain law. Alloy II.

of cycle symmetry can be seen in Fig. 3b, c, while Fig. 4 shows the effect on work that is the result of deviation of the T–γ diagrams from the optimum. Finally, Fig. 5 shows the curves which demonstrate the effect that strain amplitude (curve 1) and cycle asymmetry (curves 2 and 3) have on the energy properties of the MEC. We can see that both an increase in the strain amplitude and a reduction in this quantity lead to a reduction in the useful work (curve 1). Unlike the work shown in Fig. 2, the work here does not diminish in dependence on the number of cycles, but rather, conversely, increases and reaches a constant value for the optimum cycle (curve 2) or on attainment of the maximum drops off virtually to zero for the nonsymmetric cycle (curve 3).

The reasons behind this sharp improvement in the MEC properties for the case of the sign-variable cycle are analogous to those for the cycle shown in Fig. 1c. It is easy to see that as the optimum regime is achieved there are significant reductions in the stresses required to produce the channel of martensite inelasticity, and the capacity for reversible strains is increased, as are the reactive stresses.

The data covered above give evidence of the outstanding complexity involved in the laws governing the formation of limit thermomechanical (thermodynamic) cycles in martensite energy converters. A positive result may be achieved only through special combination of strain, force, and temperature parameters in the phase diagram and in the physicomechanical properties of the alloy. At the same time, to explain the derived results does not require resort to any special or little-studied properties of such materials. All of the fundamental quantitative relationships can be interpreted

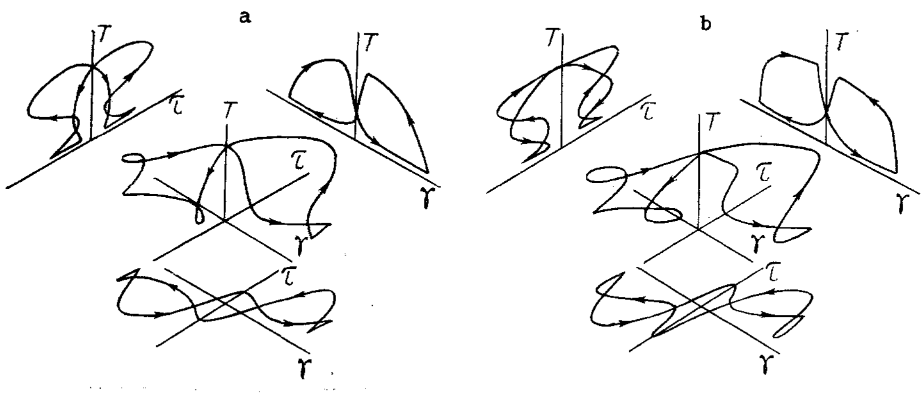

Fig. 6. Phase portraits: experimental, for alloy II (a), and calculated by the methods of the structural-analytic theory for hypothetical materials (b).

in natural terms within the framework of that portion of structural-analytic theory which describes the effect of shape memory [12, 13]. We calculated the thermomechanical cycles on the basis of the methodology covered in [12, 13] insofar as this relates to the isothermal regimes employed here. In accordance with [12, 13] it was assumed that the following assertions are valid: 1) the phase composition of the material is determined by the effective temperature, which is a function of the instantaneous temperature and the mechanical stress which displaces the characteristic temperatures of the martensite reactions in accordance with the Clausius–Clapeyron principle; 2) microplastic distortions are identical to distortions of the martensite conversions; 3) the macroscopic deformation is equal to the statistical sum of the microdeformations.

As has been established, such assumptions are adequate to describe the above-cited data, and not only in complete qualitative agreement, but also in satisfactory quantitative agreement, between the theoretical and experimental results. A detailed exposition of this study will be undertaken in a separate communication; here we will limit ourselves only to the illustration in Fig. 6, which represents the experimental and theoretical phase portraits, analogous to the phase portrait shown in Fig. 3a. Here it should be underscored that the detailed quantitative description demands consideration of the deformation that comes about as a result of twinning and dislocation slippage. This can be accomplished within the framework of the ideas expressed in [12, 13]; however, the resulting refinement imparts no changes of a fundamental nature.

As regards efficiency, the above-described methods to increase MEC efficiency make no provision, at maximum efficiency, for the possibility of simultaneously achieving the highest levels of equipment efficiency. The calculated efficiency values for the isothermal cycles in the case of the titanium nickelide do not exceed approximately 9%. However, the experimentally measured efficiency varies from 0 to 8%, although in the majority of cases it does not exceed 4%. Efficiency depends significantly on the thermodeformation regime for the martensite engine. Among the cycles shown in Figs. 1-5, it is at a maximum for the cycle shown in Fig. 3a. Let us further stress that efficiency can be significantly increased through transition to Carnot cycles. In the case of the titanium nickelide for an idealized Carnot cycle the calculated efficiency is equal to 24%. Apparently this corresponds to the maximum efficiency value which can be achieved in a specific piece of equipment. The significantly higher efficiency values noted by other authors [14] are doubtful.

The information provided here allows us to regard as possible the development of a productive engineering theory for martensite energy converters.

CONCLUSION

1. We have studied the limit thermomechanical cycles of energy converters with working media of materials exhibiting the shape memory effect and we have optimized these cycles in order to achieve maximum useful work.

2. It has been established that the best operational efficiency is dependent on the method used to produce the strains or by resorting to sign-variable symmetrical cycles in conjunction with complete attainment of phase plasticity, either through synchronization of direct and reversible martensite reactions within the interacting working media.

3. The possibility has been established for the calculation of phase diagrams on the basis of structural-analytic theory.

4. On the basis of the research carried out we can hypothesize scientifically founded principles of designing martensite engines and drives with specified operating efficiency parameters.

NOTATION

A_S, A_E, M_S, M_E, characteristic temperatures for the start (A_S) and end (A_E) of the reverse reaction, the start (M_S) and the end (M_E) of the direct reactions; T, temperature; τ, shearing stress; γ, angular strain.

LITERATURE CITED

1. V. A. Likhachev, S. L. Kuz'min, and Z. P. Kamentseva, *The Shape Memory Effect* [in Russian], Leningrad (1987).
2. I. N. Andronov, S. L. Kuz'min, and V. A. Likhachev, *Problemy prochnosti,* No. 11, 23-26 (1983).
3. S. P. Belyaev, V. A. Likhachev, Yu. I. Patrikeev, and A. I. Razov, "Reversible shape memory and its utilization in heat engines," Dep. in VINITI, December 10, 1984, No. 7870-84.
4. V. A. Likhachev and S. R. Shimanskii, "Effect of the TiNiNb composition on its properties and efficiency," Dep. in VINITI, December 10, 1984, No. 7865-84.
5. S. P. Belyaev, S. L. Kuz'min, and V. A. Likhachev, *Problemy prochnosti,* No. 6, 77-80 (1984).
6. I. N. Andronov, S. P. Belyaev, S. L. Kuz'min, et al., *Vestnik LGU, Ser. mat. mekh. astr.,* No. 1, 54-59 (1985).
7. S. P. Belyaev, S. L. Kuz'min, V. A. Likhachev, and V. F. Mozgunov, "An investigation into the efficiency of a rotor-driven martensite engine," Dep. in VINITI, April 11, 1985, No. 2427-85.
8. V. A. Likhachev, *Izv. vusov Fizika,* No. 5, 21-40 (1985).
9. V. A. Likhachev, V. L. Rassokhin, and S. R. Shimanskii, "An investigation into a composition based on titanium nickelide as the working medium in a step martensite engine," Dep. in VINITI, July 9, 1986, No. 4967-86.
10. V. A. Likhachev and A. I. Razov, *The Physics of Strength and Plasticity* [in Russian], Leningrad (1986), pp. 103-111.
11. T. A. Buldakoa and A. I. Razov, "Titanium nickelide as the working medium of a martensite energy converter with antiphase-interacting elements," Dep. in VINITI, October 25, 1988, No. 7651-B88.
12. V. A. Likhachev and V. G. Malinin, *Crystal Defect Structure Computer Simulation* [in Russian], Leningrad (1987), pp. 112-131.
13. V. A. Likhachev and V. G. Malinin, *Izv. vuzov Fizika,* No. 6, 73-78 (1988).
14. H. C. Tong and C. M. Wayman, *Met. Trans.,* 6, No. 1, 29-32 (1975).