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Modeling the magnetic field control of phase transition in ferromagnetic shape memory alloys

Anatoli Rogovoy*, Olga Stolbova

Institute of Continuous Media Mechanics, Ural Branch, Russian Academy of Sciences, 614013 Perm, Russia

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ABSTRACT

In the framework of finite deformations a model has been constructed to describe the process of controlling the austenite-to-martensite phase transformation in ferromagnetic polycrystalline materials with shape memory properties (Heusler alloys) under the action of temperature, force and magnetic fields. The control of the phase transition is realized with the help of the magnetic field, which changes (shifts) the specific transformation temperatures. The kinematic and constitutive equations, satisfying the principles of thermodynamics and objectivity, have been developed both, for the martensitic and austenitic phases and also for the mixed austenitic–martensitic state, which takes place in the process of smeared phase transition of the first order. The last is considered as a sequence of the point first-order phase transformations. Relations, describing the shift of characteristic temperature of the phase transition according to the generalized Clausius–Clapeyron law, have been derived. This shift is defined by the stresses generated in the body in the process of its deformation and is controlled by the internal magnetic field induced in the material by the external magnetic field. Moreover, the internal magnetic field produces in the body the mass (ponderomotive) and surface forces in addition to ordinary external forces of another physical nature. Deformation of the body under the influence of all forces, including the above mentioned ones, and the internal magnetic field, induced in the material, disturb the external magnetic field. To solve this connected magnetomechanical problem two connected variational equations have been used. One of these equations is the well-known Lagrange variational equation and the other corresponds to a weak formulation of the problem considering the behavior of a magnetizable body of finite geometry located in the space, which is under the action of the magnetic field, and takes into account the surface magnetic effect. The procedure for numerical implementation of these equations has been described. The model and variational equations have been used to solve the problem, in which the austenite-to-martensite phase transformation in the specimen made of polycrystalline Ni–Mn–Fe–Ga alloy (ferromagnetic shape memory material) is realized at fixed external temperature due to shift of specific phase transition temperature induced by the magnetic field. The available experimental data for this problem have been used to verify the proposed model.

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* Corresponding author. Fax: +7 342 2378487.
E-mail address: rogovoy@icmm.ru (A. Rogovoy).

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1. Introduction

Ferromagnetic alloys, in which the shape memory effect is observed (Heusler alloys), refer to the class of functional (smart) materials. Constructions made of such materials may significantly change their configuration under the action of external thermal, magnetic or electric fields. Recent studies on this subject have revealed two different physical mechanisms responsible for initiation of large strains (up to 10%) under the action of external force and magnetic fields. One of them is related to the reconstruction of structural domains in the martensitic phase and is observed in monocrystalline materials or highly texture-oriented polycrystalline samples (Buchel'nikov et al., 2006; Chen et al., 2014; Entell et al., 2008; Lagoudas, 2008; Planes et al., 2009). In the absence of the applied mechanical load the austenite-to-martensite forward (direct) phase transformation from a cubic high-temperature phase (austenite) to (as one of the variants) a tetragonal low-temperature phase (martensite) leads to the formation of several twin-related “self-accommodated” variants of martensitic state (structural domains). During this process a change in the symmetry of crystal lattice domains induces strains, which, when being averaged spatially over the material representative volume composed of a certain number of structural domains, lead only to inessential macroscopic volume strain. Structural domain, in turn, is divided into magnetic domains, in which the magnetization vectors have different directions: in each magnetic domain this vector is directed along the easy magnetization axis of this domain, and the domains are organized in such a way that they minimize the magnetostatic energy of the structural domain (martensitic variant). The application of an external magnetic field to ferromagnetic alloys causes the motion of magnetic domain walls, rotation of the magnetization vector and, provided the magnetic anisotropy is high, martensite reorientation (Chen et al., 2014; Lagoudas, 2008; Planes et al., 2009). The first two processes also occur in conventional ferromagnetic materials while the last process is inherent only in the shape memory alloys: the application of an external magnetic field to a material in the martensitic state (just as the application of the force field) leads to a rotation of the structural domains (motion of the twin boundaries) such, for the considered case, that their easy magnetization axes become aligned with the magnetic field induced in the body. Coherent reorientation of a certain number of the martensitic variants leads to detwinning of martensite and is accompanied by the macroscopic strain, which in some ferromagnetic alloys can be extremely strong. In the case when the magnetic field is removed the strain generated by rotation of martensitic variants is not recovered but partly or completely vanishes when the material is transferred into the austenitic state in the range of phase transition temperature. This deformation mechanism is not directly related to the austenitic-to-martensitic phase transformation as opposed to the mechanism considered below, and in the following the resulting strain will be referred to as the magnetic field-induced strain (MIS).

Another mechanism of significant macroscopic strain generation in materials is related to a direct temperature phase transition from the austenitic state into martensitic state due to application of the mechanical stresses. This mechanism takes place both in monocrystals and polycrystals (Buchel'nikov et al., 2006; Chen et al., 2014; Cherechukin et al., 2001; Entell et al., 2008; Haldar et al., 2014; Lagoudas, 2008; Planes et al., 2009). According to it, the formation of type of martensitic variant entirely depends on the stress field direction, so that in this case no other kind of strains can occur except for strains which are oriented in compliance with this stress. These strains are called the phase strains and complement the ordinary strains occurring in materials due to applied forces. Averaging the phase strains over the representative volume of the material leads to macroscopic strain, which will be referred to as a transition-induced strain (TIS). This strain can be considerably higher than the ordinary strain mentioned above and unlike the ordinary strain is not recoverable after material unloading. The application of the magnetic field to the material in the martensitic state, (which is the result of the previous process) may start the process of MIS reproduction discussed above. As in the previous case, a reverse material transformation into the parent austenitic phase but in the temperature range of the austenitic transformation, leads to a partial or total disappearance of all (TIS and MIS) accumulated strains and the structure regains its original shape partly or fully.

In addition, it should be mentioned that the giant magnetocaloric effect, associated with the generation or absorption of large amount of latent heat, is observed in the Heusler alloys at its transition from the austenitic to martensitic phase and vice versa (Buchel'nikov et al., 2006; Shavrov et al., 2001).

The ability of metals (alloys) to recover their original shape is called the shape memory effect (SME) and the alloys themselves are called the shape memory alloys (SMA). Based on the above considerations we have identified the main distinctions of the MIS and TIS in the Ni—Mn—Ga ferromagnetic Heusler alloy.

1. Large strains can be induced in the material either by the impact of the magnetic field on the structural domain in the martensitic phase only or as a result of the austenite-to-martensite phase transition process, which is realized under the action of the force field.
2. The shape memory effect, which can be controlled with the help of magnetic field, is observed both for MIS and TIS.
3. The magnetic field required to control the shape memory process is by 1 or 2 orders of magnitude greater than the magnetic field required for reconstructing the structural domains in the martensitic phase.
4. Magnetic control of the shape memory effect in the ferromagnetic alloys is a more inertial process than the process of reconstruction of structural domains in the martensitic phase. This can be attributed to the characteristic times of generation or absorption of considerable quantity of latent heat during the phase transition.
5. The sample with TIS can do considerably more mechanical work and can change its shape more dramatically than the sample with MIS.

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