

Progress through Mechanics The Martensitic Phase Transformation

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The shape memory effect that occurs in some metallic alloys has been studied extensively by materials scientists since its discovery in the 1960s. After undergoing a plasticity-like deformation, these alloys return to their original shape when heated above a certain critical temperature. Advances in the understanding of these materials could lead to practical applications in diverse fields. Common uses of shape memory alloys today, like artery- or colon stents [11] and even eyeglass frames, utilize the high temperature phase only, where elastically reversible deformations of up to 6% length difference can be achieved. Materials exhibiting this shape memory behavior include nickel-titanium alloys as well as copper-aluminum-nickel and copper-zinc-aluminum. The effect has recently received much attention as a possible source of actuation in micro electro-mechanical systems (MEMS) [4], due to the fact that the work output per unit volume of phase-transforming materials is the largest among possible actuator systems [10].

Micro electro-mechanical systems integrate sensors, electronic circuits and actuation on a single chip, usually silicon based. For example, an application already in use today is that of digital light projection displays, where hundreds of mirrors that can be individually moved are attached to the surface of a silicon wafer. The possibilities range much further though. Implantable insulin pumps for diabetics are currently under development. The integration of sensors and microscale pumps in these systems would help achieve previously impossible accuracy in administering the drug. Currently, there is also research being conducted on neural prosthetics that directly communicate with nerve cells by inserting a movable electrode. These applications have one thing in common. They require strong, highly accurate, and bio-compatible microscale actuators that can easily be attached and linked to microchips. Electrostatic actuators in current use lack these properties, however, shape memory materials—like nickel-titanium—could solve the problem. The idea is to deposit a single crystal film of shape memory material onto a substrate and add a temperature controlling element to enable interaction with the other components of the device. A small area of the substrate underneath the film is then removed by back-etching to give a free standing thin film of phase-transforming material that is bonded on all sides. If certain crystallographic conditions are satisfied, the thin film can

be cycled between a flat and a tent like structure, performing as a micro- or nanoscale pump or valve [6].

Space exploration provides another possible use for phase-transforming martensitic materials. The challenge is to integrate structure and actuation in order to build large foldable devices with very low mass. Once the structure is deployed into space, the solar panels and antennas need to unfold. Shape memory materials could provide the necessary means of actuation, while afterwards serving as structural parts of the device and providing stability.

These applications bring many challenges in the field of mechanics. The interplay of surface and phase boundary energies with complex multi-well strain energies leads to microstructure. Materials scientists have characterized the various types of such microstructure, but the use of shape memory alloys as actuators requires more knowledge about the properties of its evolution. It is not clear, for example, what kinetic law relates the velocity of a domain boundary between two martensitic variants with the thermodynamic driving force from loading. Also, the interaction of such domain walls with crystallographic defects is thought to have great influence on the kinetic parameters of the pseudo-plastic deformation [2], yet it is not well understood in domains of more than one dimension. The design of complex structures with highly nonlinear materials also leads to many new challenges. The tents formed by martensitic thin films [1] can for example be examined numerically [7]. New and unexpected buckling modes have been discovered in stents made of nickel-titanium. Foams of shape memory materials are being investigated for their properties of impact energy absorption.

Microscopically, the shape memory effect is caused by a reversible diffusionless phase transition, the so-called martensitic phase transformation. The material is characterized by a low symmetry crystal group in the low-temperature phase, the martensite, while the high-temperature phase, the austenite, exhibits a higher symmetry. Without any applied load, there is always more than one stable martensitic phase. These energetically equivalent variants of martensite are related by the symmetry operations of the high symmetry phase [3]. In the continuum description, the symmetry properties lead to a complex energetic landscape, the modeling of which is an interesting problem in its own right [8]. Consider for example nickel-titanium alloys. The austenite phase is of cubic crystallographic symmetry, and there are 12 variants of the monoclinic martensitic phase. Let us assume that in the unstrained original configuration, all variants occupy an approximately equal volume fraction of the crystal. This situation is called the twinned state. Under an applied load, however, the variant that is most compatible with the load is preferred and will increase in volume fraction. This leads to a plastic deformation of the crystal. After heating the material above the critical temperature, the body returns to its original shape because now only the single cubic phase is stable. It is this direct coupling of temperature, crystal structure and macroscopic deformation that is responsible for unique properties of martensitic materials. Twinning will reoccur upon lowering the temperature again.

The research on shape memory materials has led to advances in several

other areas of interest. The knowledge of microstructure and its evolution is vital for the understanding of plasticity [5]. Ferroelectric materials exhibit a highly nonlinear coupling of the deformation of a material to an applied electric field and are studied using similar techniques. The essential nonlinear nature of the phenomena involved in the shape memory effect also calls for new mathematical methods to investigate the resulting models. The applications of martensitic materials are not restricted to metallic shape memory alloys. Complex protein structures undergo the same kind of phase transformation and can be understood through mechanics [9]. These bio-nano actuators could lead to considerable advances in medicine. These prospective applications make shape memory materials a very promising area of research.



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