Magnetoelastic materials

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Introduction

In magnetoelastic materials an external magnetic field can change the elastic properties and the extension of a magnetic material. This can be used either directly for actuation or the reverse effect allows for sensing and energy harvesting. Goal of this lecture is to explain the different underlying physical concepts of magnetostrictive materials and magnetic shape memory (MSM) alloys. This includes a short excursion to diffusionless phase transformations, which is also needed to understand magnetocaloric materials. With some examples it will be illustrated how these materials can be implemented in devices.
Most of the following is taken from 1), which gives a state of the art summary of magnetic shape memory alloys.

Main Body

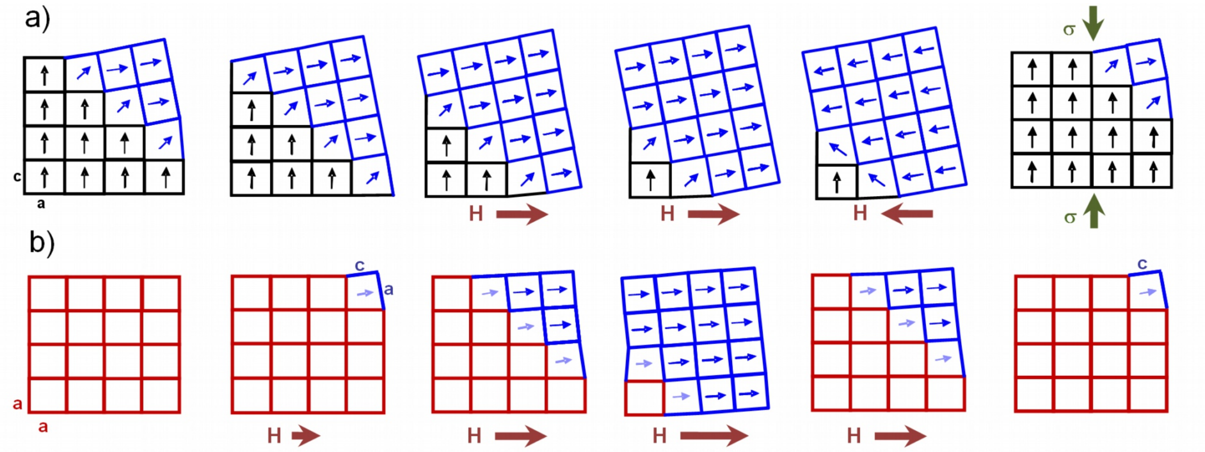

Figure 1: Controlling microstructure (a) and structure (b) of magnetic shape memory alloys by magnetic fields. a) During Magnetically Induced Reorientation (MIR) the magnetic field H moves twin boundaries in a way that variants with their easy magnetization axis parallel to the external field (blue) are favored compared to those aligned perpendicularly (blue). Since the easy axis coincides with the short c-axis the sample shrinks along the field direction. Using negative field direction does not affect variant orientation. However, for reversible actuation with strains up to 10% the original state can be restored by mechanical stress σ, which aligns the short c-axis. b) During a Magnetically Induced Martensite (MIM) transition the magnetic field induces the martensitic phase, exhibiting a higher magnetization. The sketch illustrates the movement of the austenite(red)/martensite(blue) phase boundary. When removing the magnetic field the original austenitic state is restored.

In magnetoelastic materials there are different ways of coupling between magnetism and crystal lattice. In magnetostrictive material spin-orbit coupling allows to change the orbits and thus the distance between the atoms when changing the direction of the magnetic field. This allows obtaining strains up to 0.24% in low magnetic fields and with reasonable forces.

Magnetic shape memory (MSM) alloys can reach strains of up to 10%, which are about two orders of magnitude more than common magnetostrictive materials and the piezoelectric materials applied today. Since MSM materials can be driven with frequencies up to the kHz regime, the unique combination with very large strain and high energy density allows for novel applications, which are not feasible using other adaptive materials. Due to the large strain MSM actuators often can be used directly, without any complex mechanical amplification. This is of particular importance for micro actuators and sensors, where things have to be kept simple.

MSM alloys are one of the rare materials where a relatively small energy input supplied by moderate magnetic fields is sufficient to control the sample's microstructure. The underlying mechanism, Magnetically Induced Reorientation (MIR) of martensitic variants, is sketched in fig. 1a. Starting point is a twinned martensitic microstructure, which had been formed by a diffusionless transformation. This microstructure consists of variants with different crystal orientation, which are connected by twin boundaries. In case of materials with large magnetocrystalline anisotropy it can be energetically favorable to move these twin boundaries in order to orient variants with their easy magnetic axis towards the direction of the external field. During MIR the crystal structure remains the same since only the orientation of the unit cell is affected. As the crystallographic axes differ in length, the extension of the sample is changed by the magnetic field. MIR requires highly mobile twin boundaries. Indeed in the best samples twin boundaries can be moved by a fraction of a MPa. This means that you can deform these samples with your fingers like rubber − though they are a metal. This is in strong difference to steel – another ferromagnetic material, where martensite formation is used for hardening.

Also the sample structure can be controlled by a magnetic field. The Magnetically Induced Martensite (MIM) effect is sketched in fig. 1b. In case that the martensite exhibits a higher magnetization compared to the austenite, an external magnetic field favors the martensite phase by thermodynamics. Though this structural transformation may also be used for high force actuation, it is more promising to use the associated latent heat of this first order transformation for magnetocaloric refrigeration. For this type of application so-called metamagnetic martensites are of particular interest. In these materials the magnetic state changes with the structure such that the austenitic phase exhibits a substantially higher magnetization compared to the martensite, hence one obtains a Magnetically Induced Austenite (MIA) effect.

References

1. *Special Issue: Magnetic Shape Memory Alloys, Adv. Eng. Mat. 14(8) (2012)*
2. *B. D. Cullity, C. D. Graham, Introduction to Magnetic Materials, 2nd Ed. Wiley, (2009), Chapter 8: Magnetostriction and the effects of stress*
3. *A brief introduction on magnetic shape memory alloys with animated gifs: http://www.magneticshape.de/funktionsprinzip.html*
4. *Slides of a previous tutorial: http://magnetism.eu/esm/2007-cluj/slides/doerr2-slides.pdf*