Study of magnetic field distribution in anisotropic single twin-boundary magnetic shape memory (MSM) element in actuators

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Abstract. Magnetic shape memory effect exhibited by certain alloys at room temperature is known for almost 20 years. The most studied MSM alloys are Ni-Mn-Ga alloys which exhibit up to 12% magnetic field-induced strain (change in shape) depending on microstructure. A multibillion cycle operation without malfunction along with their "smart" properties make them very promising for application in electromagnetic (EM) actuators and sensors. However, considerable twinning stress of MSM crystals resulting in magneto-mechanical hysteresis decreases the efficiency and output force of MSM actuators. Whereas twinning stress of conventional MSM crystals has been significantly decreased over the years, novel crystals with Type II twin boundaries (TBs) possess even lower twinning stress. Unfortunately, the microstructure of MSM crystals with very low twinning stress tends to be unstable leading to their rapid crack growth. Whilst this phenomenon has been studied experimentally, the magnetic field distribution in anisotropic single twin-boundary MSM elements has not been considered yet. This paper analyses the magnetic field distribution in two-variant single twin-boundary MSM elements and discusses its effects on magnetic field-induced stress acting on the twin boundary.

1. Properties of MSM alloys important for actuation

Properties of MSM alloys are constantly improving. The reversible magnetic field-induced strain as large as 12% reported in [1] doubles the most common 6% maximum strain of first successful Ni-Mn-Ga specimen [2]. Another parameter of immense importance is twinning stress which is related to energy required for propagating twin boundaries changing shape of the MSM element. This parameter is particularly important for MSM actuation due to its relation to internal friction [3]. Pure crystals with low 0.3-0.5MPa twinning stress were reported in [4]. These values are currently attributed to the most common Type I TBs [5]. However, Type II TBs with remarkably low 0.01MPa twinning stress and corresponding 30mT switching field were reported in [6]. These crystals are particularly promising for actuation due to very high efficiency of magneto-mechanical energy conversion. On the other hand, several important aspects of the shape change in Twin II MSM elements reported in [7, 8] question the long lifetime stability of these crystals. Whilst the response of a single twin-boundary MSM specimen to mechanical stresses has been previously studied, the effects related to non-uniform nature of the magnetic field distribution due to non-homogeneity of MSM microstructure and magnetic anisotropy of its twin variants have not been analysed yet.

Twin boundaries of both types can exist in the same specimen depending on the condition of their nucleation. However, very low twinning stress is obtained only when a single Type II TB is present. This is distinctly different from the behaviour of Type I TBs which tend to form lamellar structures called fine twins [7, 9]. The concentration of all variants of the same type on one side of a single twin boundary results in a very non-homogeneous magnetic field distribution, especially when anisotropy of MSM permeability is taken into account.

2. Magnetic field distribution in a single twin-boundary MSM element

The analysis summarised in this paper is based on finite element (FE) analysis implemented using commercially available ANSYS Multiphysics software package. Hence, only the magnetic vector potential (MVP) formulation of Maxwell's equations is used in all models. An advantage of such approach is its compatibility with design methodologies available for MSM sensors and actuators [10]. Whereas modelling of variant distribution has been previously discussed [10], magnetic anisotropy of twin variants is usually omitted in existing modelling approaches. However, the overall magnetic anisotropy of MSM element is a consequence of anisotropy of its twin variants. Therefore, each axis in a variant should be assigned with its own magnetisation curve in order to take magnetic anisotropy into account correctly. The modelled MSM element possesses the most studied 5M microstructure [2]. Its saturation magnetisation is 0.69T and initial relative permeability of "easy" and "hard" axes are 50 and 2. The MSM element is blocked in order to prevent variant growth.

Figure 1 shows the non-uniform magnetic field distribution in a single twin boundary MSM element in a strong 0.6T applied magnetic field. A short 2.5mm × 1mm MSM element is used for clarity of the figure. The magnetic field is applied transversely to its longest 2.5mm side resulting in 2.2% elongation. A "hard" variant with *a* axis along the applied field is allocated above the "easy" variant with *c* axis along the field. It should be noted that both variants still possess anisotropy which implies that the "hard" variant has its *c* and the "easy" variant has its *a* axes normal to the applied field. However, Fig. 1 shows that the field lines change direction inside the MSM element. This happens due to the 45° angle between the TB and the MSM element's sides. This results in both transverse (x) and longitudinal (y) components of the magnetic field in MSM twin variants. However, it is known that longitudinal magnetic fields induce compressive stresses in MSM crystals. A non-uniform magnetic field causing a complex stress distribution in a multi-variant MSM specimen was studied in [11]. Similarly, the non-uniform field distribution in Fig. 1 can be one of the reasons for nucleation of TBs oriented differently than the main (modelled) propagating TB in single twin-boundary MSM elements. This can lead to instability of their microstructure.

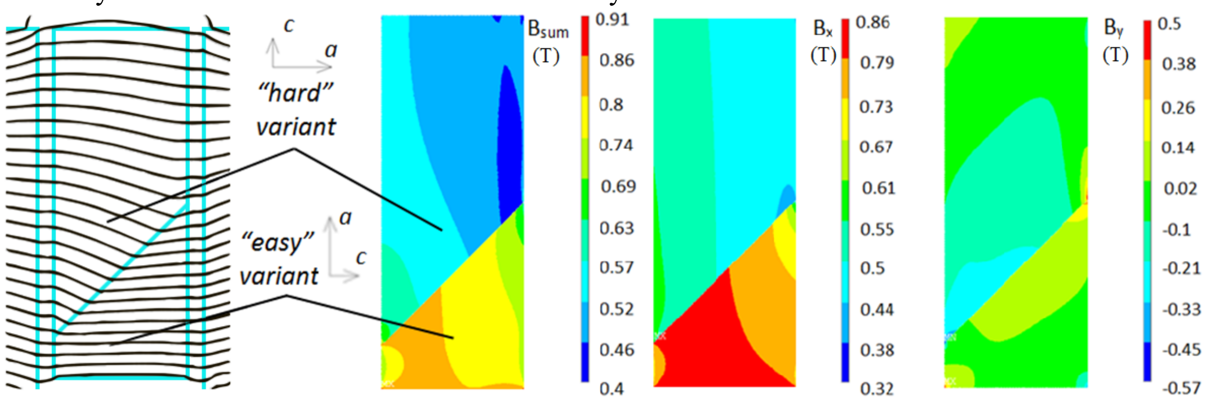

Figure 1. Magnetic field distribution in a single twin-boundary MSM element subjected to a strong applied field.

Figure 2 (a) shows the magnetic field distribution in the same MSM element in a weak applied field not exceeding 0.1T. The effects related to variant anisotropy become even clearer since variants are not saturated. Here, flux lines tend to locally align with the "easy" axis in each variant. This is consistent with the basic theory of the MSM effect. The most interesting point lies on the left side of the TB in Fig. 2 (a), where magnetic flux density inside the MSM element reaches 0.67T due to internal magnetisation of its twin variants. One can observe the general decreasing trend in magnetic flux density along the length of the twin boundary. It is also remarkable that the difference exceeds one order of magnitude, implying greater strains on the left side of the MSM element in comparison with its right side.

It should be also noted that this effect is not as apparent when isotropic twin variants are modelled. Figure 2 (b) illustrates this. Although the general pattern of field distribution remains unchanged, its magnitude is much lower. Therefore, it is significantly important to model anisotropy of MSM twin variants correctly.

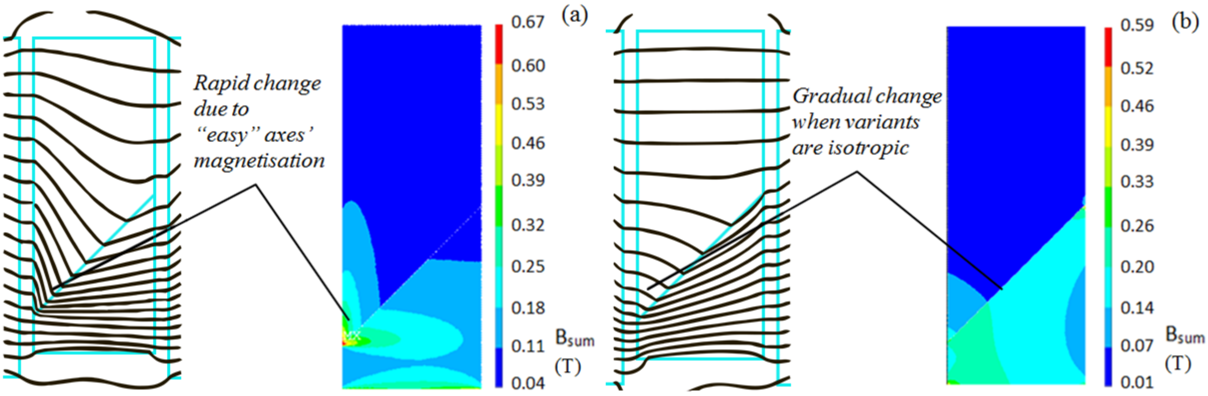

Figure 2. MSM element in a weak applied field with (a) anisotropic and (b) isotropic twin variants.

3. Conclusions

The magnetic field distribution in non-homogeneous two-variant MSM element is studied with FE analysis and its very non-uniform nature is discussed. In addition to non-homogeneity of field distribution which was clearly observed in both weak and strong applied fields, it was also possible to locate a point of particularly high magnetic field energy concentration in a sufficiently weak magnetic field. This result also suggests very non-uniform distribution of mechanical stresses due to magneto-mechanical coupling leading to their concentration in specific areas of the MSM element, supporting findings previously reported by other researchers. The importance of accurate modelling of variant anisotropy is illustrated by comparing the computational results obtained on anisotropic and isotropic twin variants. Further work will include a detailed study of distribution of magnetic field-induced stresses and their effect on the total force acting on the twin boundary, which translates into output force in actuators.

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