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Review of properties of magnetic shape memory (MSM) alloys and MSM actuator designs

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Abstract. Magnetic shape memory alloys are a new group of "smart" materials that exhibit large strain of 6-12% when subjected to magnetic fields. This indicates their enormous potential to be used in different electromagnetic (EM) devices such as actuators, sensors, energy harvesters and dampers. Shape change in MSM materials is controlled by magnetic field and doesn't involve phase transformation, allowing it to overcome a number of disadvantages of conventional shape memory alloys (SMAs). MSM devices are capable of producing large force and stroke output in considerably small dimensions. At the same time they can have fast response and potentially very long lifetime. This paper discusses different modern designs and approaches to MSM actuator design with their advantages and disadvantages. An overview on characteristics of MSM alloys is also presented in order to highlight how different properties of the material influence the total output of a device.

1. Introduction

Magnetic shape memory alloys (MSMAs) or ferromagnetic shape memory alloys (FSMAs) form a new group of shape memory materials in which a shape change can be controlled by the application of a magnetic field or an external stress. Ni-Mn-Ga alloy is the most studied representative of this alloy family and it has been shown to have enormous potential for real applications. Although the material is still at R&D stage of its development and applications, its properties have been significantly improved in recent years since the low-field magnetic shape memory effect was discovered in 1996 [1]. MSM alloys are well-known for their enormous magnetic field induced (MFI) strain, maximum theoretical value of which varies depending on material's microstructure from 6% for five-layered modulated (10M) to 12% for non-modulated (NM) alloys [2,3]. These strain values are higher than maximum strains achievable by conventional magnetostrictive and piezoelectric materials and are of the same order as strains obtained from conventional shape memory alloys (SMAs). However, MSM alloys respond to excitation much faster because the shape change occurs with no phase transformation unlike in conventional SMA materials. The main potential applications of MSM materials could be sensing, damping, energy harvesting and especially high-performance electromagnetic actuation at a frequency range up to a kHz. This paper overviews MSM actuator designs proposed so far and the properties of MSM alloys that are relevant for this application.

2. Effects of twinning stress on performance and efficiency

The nature of MSM phenomenon is extensively discussed in literature [4]. When MSM material is subjected to a magnetic field its unit cell can be reoriented producing a strain the maximum value of which is determined by lattice distortion $\varepsilon_0 = 1 - c/a$, where c and a are "easy" and "hard" magnetization axes respectively. Maximum value of MFI stress is limited by crystal's anisotropy energy and is usually considered to be 3 MPa [4] for 10M microstructure though 3.5 MPa was also reported [5]. One of the most important parameters of MSM alloys for their use in actuators is twinning stress, which is a stress to be overcome in order to initiate the shape change. Due to magneto-mechanical coupling, this parameter determines switching field of the crystal (the lowest field at which the shape change occurs). The twinning stress acts as internal friction which decreases the maximum output stress of an MSM element (the so called MSM 'stick') and, hence of an actuator based on MSM alloy. Conventional MSM crystals with type I (twin I) boundaries have a twinning stress of the order of 0.6MPa [6,7]. However, new crystals with type II (twin II) twin boundaries have been reported recently [8,9] with twinning stress less than 0.1 MPa. Such a low twinning stress can lead to corresponding increase in output force coupled with a decrease in required power input enhancing at the same time efficiency of an actuator. Unfortunately, this microstructure is still very unstable and tends to accommodate other twin boundaries which increase twinning stress and dramatically decrease fatigue life of a crystal [6].

The magneto-mechanical characteristics of MSM alloys are very sensitive to temperature. The twinning stress of type I twin boundaries tends to decrease as temperature increases [10]. This may have a tremendous effect on performance parameters, such as increase in strain or output stress with temperature at a constant magnetic field [11] and a decrease in switching field [12]. This may imply that MSM alloys can be used most effectively at high temperatures. However, the current thermal operational range of these crystals is limited by a temperature range of 60-80°C [13, 14] which is rather low for most high-frequency and long-lifetime applications. Due to electric and magnetic losses in various parts of an actuator including the MSM element, excessive temperature rise can lead to the disappearance of MSM effect. The increase of this transition temperature is very important since this temperature essentially defines the operational magneto-thermal limitation of an MSM alloy. Hence much research is being conducted at present by materials researchers to increase this temperature. Also it should be noted that even if the upper temperature limit for twin II crystals is the same as for twin I, the twinning stress of these crystals doesn't depend on temperature [15]. This essentially implies that the characteristics of actuators based on twin II crystals are more stable. However, magneto/electro-mechanical fatigue life of MSM alloys should also be considered.

Theoretically MSM alloys are capable of delivering very long fatigue life. However, this is very much dependent upon its microstructure and operational regimes. Over the years there has been steady improvement in fatigue life from the mere 200×10^6 cycles in 2002 [28] to 2×10^9 in 2010 [6]. This means that it is possible to design MSM devices with very long lifetime. However, two important considerations need to be taken into account to achieve this. Firstly, MSM crystals with low twinning stress were found to be much more brittle with a fatigue life less than 10^7 cycles. This means that twin I crystals with higher twinning stress are more promising for long lifetime devices. Secondly, the operational regimes need to be designed in such a way as to prevent the MSM element transiting into a single-variant state (fully elongated or fully contracted). Although this slightly decreases available stain but it makes very long fatigue life possible.

Overall, 10M MSM alloys with type I twin boundaries can be used to design long lifetime devices with average efficiency, whereas crystals with type II boundaries can be used for very compact and efficient devices with a limited fatigue life. At present crystals with 10M microstructure are considered to be the best for actuation devices as they have high MFI strain and stress accompanied by low twinning stress. This microstructure is the most studied and all designs discussed are based on the use of these crystals.

3. MSM actuators

All MSM actuator designs are based on design elements used as sources of excitation and restoring forces. Almost all possible combinations suitable for actuators are discussed by Holz *et al* [16-18] where each combination is called an "operation mode". Two of them, corresponding to magnetic elongation along with mechanical contraction and only magnetically controlled shape change are discussed in details. The former represents the most common design feature of MSM actuators: a magnetic field produced by coils and/or permanent magnets (PM) controls the elongation of the MSM element in one part of a cycle whereas a mechanical force, which is usually produced by a spring, contracts it in the other part of the cycle. Actuators of this type are the most studied. The main disadvantage of this design feature is reduced maximum force of an actuator as mechanical spring should be strong enough to overcome the twinning stress of a material to contract it [4]. Therefore, MFI stress is opposed by both twinning stress of the material and compressive stress of the spring used. Moreover, the spring represents a weak point from the point of fatigue life. In an alternative design a field generated, by two coils is used for both contraction and elongation depending on the direction of currents. In this case there is no uniform compressive force, thus the output force is higher. Such a design was also discussed in [19], where two coils were used to operate a thin film MSM bridge. However, this design leads to additional power demands and higher electric power losses. In a conventional system, only half of the operating cycle requires electrical excitation while the other half is operated by a spring with no electromagnetic losses and additional power demands. In a system with no spring, both parts of the cycle require current leading to extra losses and extra power consumption. Replacing the spring by permanent magnet(s) can solve the problem described above. If uniform magnetic field of permanent magnet(s) is applied along the direction of the shape change, MFI stress produced by this field will compress the MSM stick. Therefore, no additional excitation is required for contraction. However, magnetic flied inside an MSM stick produced by permanent magnets will depend on MSM permeability which is a function of strain and, hence the magnetic stress produced will not be constant. This means that during elongation the compressive magnetic stress will be excessively high which will lead to a decrease in maximum output force of an actuator by even higher amount than a spring does.

Permanent magnets can also be used to reduce supply current [20]. In this case, magnetic field of magnets is aligned with the coil field which is transversal to the MSM stick. The strength of PM field in the air gap can vary between zero and the switching field. In this case the supply current can be significantly reduced leading to smaller size and higher efficiency of an actuator. However, the PM field will produce magnetic stress which doesn't disappear when the excitation current is removed which means an extra stress to be overcome by the spring. Therefore, stronger spring is required which in turn will decrease the output stress of an actuator during elongation. This operation should be carefully considered as a possible trade-off between efficiency and output force of a device.

As mentioned above, linear actuators with electromagnetic excitation and a spring are the most common design option. The simplest design comprises an MSM stick of rectangular cross-section positioned between the poles of a suitably designed magnetic circuit and connected to a push rod of some sort. Various design variations of this kind can be found in the literature [21] including linear actuator with MSM element of cylindrical shape. Actuators of this type can be fast and small in size delivering considerable output forces. Unfortunately, the excitation coils of these actuators are still relatively large and require extra space limiting the design of very small-size devices. As twin II alloys are shown to have very low twinning stress, actuators based on these alloys can be much smaller due to reduced coil dimensions. Nevertheless, switching field of the material also depends on the total load. Therefore, actuators designed for large force output would require a higher excitation current compared to actuators designed for large stroke output under a small load. This leads to increased number of coil turns and hence, again, to larger dimensions. For actuators with twin I MSM elements, a considerable twinning stress complicates control of intermediate strains due to magneto-mechanical hysteresis [22]. However, there are a number of ways of overcoming this unfavourable property and even to turn in into an advantage.

One design option to use two MSM sticks in order to improve the accuracy of position control has led to a "push-push" actuator design [23], which is receiving a considerable attention nowadays. In this case, the moveable part is placed between two MSM sticks each of which is capable of further straining or contraction. Excitation of the coil corresponding to one of the two sticks leads to elongation of that stick with simultaneous contraction of the other, with the mechanical link moving in the direction of elongation of the first stick. If the current is removed, the actuator maintains its position due to internal holding forces of MSM elements. Therefore, excitation currents can be applied as short pulses in corresponding windings. However, the size of such an actuator tends to be much larger due to the need for two MSM sticks and two excitation coils. Also, even if no restoring force is required, twinning stress of each MSM stick lowers the output stress of the other and thus, decreases the total output force of the actuator. The "push-push" concept of MSM actuator design was behind the design of an MSM-based clamping device [24] where two MSM sticks were used to open or close a single clamping jaw.

Due to variations of length, cross-section and magnetisation during actuation, the resistivity and permeability of MSM crystals also change with the shape change depending on the current strain. This opens up ways to design a device capable of sensing its own position via the estimation of current values of varying parameters. This can be done by adding a circuitry that measures either the resistance [25] or the inductance [26] to calculate the corresponding strain. Such a self-sensing actuator possesses a closed-loop control system which significantly improves position control capability [27]. However, the size of an actuator increases due to the need to accommodate a sensing element e.g. an extra coil for measurements.

In general, the output force of an MSM stick is proportional to its cross-sectional area and the stroke is proportional to its length. An actuator producing a 1kN blocking force by a cylindrical MSM stick of 290mm diameter was presented in [28]. Also an actuator design containing five MSM sticks connected in series producing 4.5mm total stroke was presented in [29]. This illustrates design variations and the capability of MSM alloys to produce large force and large stroke outputs.

At present the main applications of MSM alloys include actuators for valves, linear motors, pumps for macro- and micro-scale applications. The design of a rotating actuator is presented in [30], where movement of a linking rod connected to two MSM sticks of a differential actuator was converted into rotation of a rotor. Application of inverse characteristics was proposed for use in sensing, energy harvesting and damping.

4. Modelling and design of MSM actuators
The structure of a basic MSM actuator is rather simple, consisting of coils, flux guide (magnetic circuit) and a MSM stick with a push-rod connected to it. Therefore, the principles used to design the magnetic circuit of electromagnetic solenoid actuators can be applied here. The only difference is that magnetic properties of MSM elements vary in magnetic field in a different way than those in conventional ferromagnetic materials. These variations turn out to be considerable affecting the entire operation of an actuator. Initially, it was suggested to linearise the magnetisation curves [31] and use the effective magnetisation curve which essentially means taking the average properties of MSM material. This resulted in an equivalent circuit model with lumped parameters which uses average MSM permeability [20]. However, some of the recent research results show that variant distribution plays a significant role in affecting the magnetic field distribution inside an MSM stick. This can be taken into account by finite element (FE) modelling and characterisation of magnetic field distribution in the magnetic circuit [7, 32]. If the average permeability is used the modelling results give good agreement with that obtained from analytical solutions. If the variant distribution is taken into account the MSM properties are represented much more accurately and local non-uniform field distribution can be modelled. It is also possible to take into account the entire magnetic circuit of an MSM actuator into one model enabling optimisation. Overall, the modelling of magnetic field of an actuator leads to significant increase in accuracy due to more accurate representation of piece-wise homogenous nature

of MSM properties. The most comprehensive approach to modelling along with experimental verification is presented in [7].

5. Conclusions

A brief overview of modern MSM actuator designs have been discussed with their advantages and disadvantages highlighted. The effects of twinning stress on actuator output force and fatigue life together with its dependence on twin boundary type have been also discussed. The variations of magnetic properties of MSM alloys have been discussed and FE modelling is proposed as a valuable design tool for taking those into account.

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