# Progress in developing smart magnetic materials for advanced actuator solutions

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**Abstract:**
Solid state actuators based on smart magnetic materials have received considerable interest over the last years because of their fast frequency response, high energy efficiency and in many cases large stroke and force output. Although this class of smart material offers new options that cannot be addressed with traditional actuator technologies, there is still progress going on in developing optimum material properties and production processes. The recent developments in materials and production technologies as well as new actuator concepts are presented in this review paper, with a focus on magnetic shape memory materials and actuators.

Keywords: magnetic shape memory, MSM production, MSM actuators, magnetostriction

**Introduction**

Materials that change their shape upon application of a magnetic field are known already from the 19th century. The term magnetostriction was first used to describe the minimal shape change of < 60 ppm in Fe, Ni and Co metals, measured by Joule in 1842. Some of the earliest uses of magnetostrictive materials include telephone receivers, hydrophones, magnetostrictive oscillators, torque-meters and scanning sonars. In fact, the first telephonic receiver, tested by Philipp Reis in 1861, was based on magnetostriction. In late 1960´s a new era in magnetostrictive materials started with the discovery of "giant magnetostrictive" TbDyFe Terfenol-D materials, capable to produce shape changes of up to 0,16 % (or 1600 ppm), putting this material on a par with typical piezoelectric transducers.
In typical actuator designs, however, not all this strain is used. The relation strain vs. driving field has a typical butterfly-shape, as has the corresponding curve in piezoelectric materials. The origin of this type of curve is the interplay of a non-linear onset of the effect, eventual saturation, sign-independence of the effect, combined with a hysteresis. Obviously, this shape is not ideal for designing actuators. The first thing to do is to identify a section of the curve that shows both, mostly linear behavior and a steep gradient of magnetostrain over driving field.
In order to operate the actuator in this regime it is necessary to introduce a mechanical preload and a bias field. This bias field might be introduced by means of permanent magnets that are placed next to the GMM active rod. The coil then only needs to generate the field variations necessary to move the working point on the butterfly curve in the chosen regime. This reduces the amount of field required from the coil, however, the magnetic reluctance of the circuit at the same time is very high, since both GMM and permanent magnets have low permeability (less than ten for Tefenol-D). For this reason, a comparatively large current linkage is required, i.e., a lot of copper, even if the housing uses high-permeability material. Thus sizable coils are still necessary, even though the bias field is supplied by permanent magnets.
Energy density (within the active material) is much higher for GMM than in a piezoelectric, by more than an order of magnitude. In order to appraise this difference, however, it is necessary to consider the overall design of a given actuator module. Generally more is required than just a block of active material, as was pointed out above.
In case of a piezoelectric transducer, the volume fraction required for the electrical contact layers might be considerably smaller than the volume fraction of piezoelectric material. Additional space is needed for contacts and a spring for the required mechanical preload and for structural parts and housing. Still, the piezoelectric material makes up a considerable volume fraction of the actuator module.
With respect to a GMM actuator, the loss in volume is considerably more pronounced, mostly due to the coil needed to generate the magnetic driving field. In relation to the actual actuator module, the superior energy density of giant magnetostrictive materials as compared to piezoelectric materials therefore is essentially evened. Similar considerations are interesting with respect to another type of magnetostrain that can occur in certain materials.
In the late 1960´s strains of up to 4 % were reported in Tb and Dy single crystals at cryogenic temperatures, due to the "reorientation of twin boundaries" [1]. The latter mechanism remained for several years un-attended, until the discovery of similar effects in non-stoichiometric single crystals

of NiMnGa in 1996 [2]. Materials called Magnetic Shape Memory (MSM) (the term Ferromagnetic Shape Memory Alloys, FSMA, is used mainly in USA to describe the same alloys) can produce shape changes of up to 10 % when subject to moderate magnetic fields of < 1 T. The research on MSM materials and actuators has grown fast over the past years, with new materials and prototype applications rapidly evolving. This is also mirrored in the amount of publications and in a new conference series, ICFSMA, focused in this field. The mechanisms of classical Joule magnetostriction and of magnetic shape memory differ considerably; they have been described thoroughly in the literature, and will not be the subject of the present review paper. The focus will be the more recently developed MSM materials, their production technology, and their applications in selected actuator and sensor examples.

## Production of MSM Materials

The best MSM performance is obtained in single crystalline rectangular elements (called also sticks). The production of these elements involves several steps: from raw material cleaning to single crystal growth, cutting and training procedures. Each step alone, as well as the whole production sequence, is important to the final quality and performance of individual MSM elements. The resource efficient production of MSM elements contributes also to the economical exploitation of these new materials. Recently, a new production approach has been introduced for the single crystal casting of NiMnGa MSM materials, using commercially available production machinery [3].

This production process involves the Bridgman type crystal growth process where large, up to 48 mm diameter and 200 mm length, Ni-Mn-Ga single crystals have been produced. These crystals are also very homogeneous as reported in [4] and further demonstrated in Figure 1.

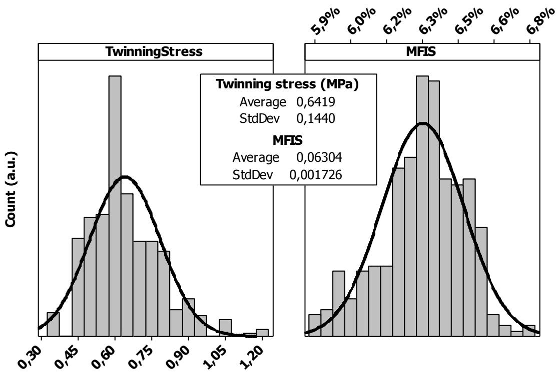



**Fig. 1.** *Histogram showing twinning stress and magnetic field-induced strain values with low scattering in MSM elements produced at ETO MAGNETIC GmbH.*

In this figure several sticks cut at different positions of the same crystal show homogeneous magneto-mechanical properties. This production process has proven also very efficient because, once developed, it can be easily upgraded to a volume production use with the same equipment.

A key to the successful production of large single crystals is the recent development of process simulation tools and the measurement of thermo-physical parameters of NiMnGa over a wide temperature range [5]. Using these data important process influencing parameters such as the temperature gradients, the position of the solidification front, and the temperature distribution within the liquid and the solid crystal have been determined, as shown in Figure 2.

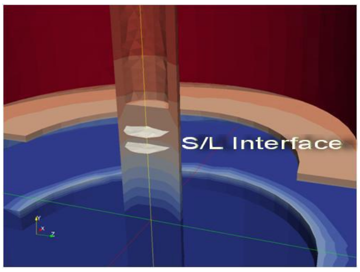



**Fig. 2.** *Process simulation revealing temperature gradients and the solid/liquid (S/L) interface during MSM production.*

An important step in the production of MSM elements is the cutting process, which considerably affects the quality and the production costs of the elements. To date electrical discharge machining (EDM) methods have proven advantageous; new cutting techniques like water jet cutting, dicing, sawing and electro-chemical cutting have recently been investigated because of their advantages in efficient volume production [6]. Each of these technologies has its advantages and disadvantages, and the selection of the optimum and economically most feasible method depends to a large extent also on the size of the material to be cut.

## Magneto-mechanical Properties

In MSM materials magneto-mechanical properties like magnetic field-induced strain (MFIS), twinning stress, effective work output, and magnetization are important when assessing the quality and performance of an MSM element.

The twinning stress is an indication of how easy or difficult the twin boundaries are moving with the application of an external mechanical stress or magnetic field. Recently, extremely low values of twinning stress have been reported in experimental samples, using ultra pure raw materials [7]. Typical twinning stress values in production type MSM materials are 0,4-0,7 MPa. In Figure 3 the stress-strain curve of MSM materials produced by ETO MAGNETIC GmbH is presented. The efficiency of these materials, as measured by the ratio of the magnetic field-induced work output to the work needed to mechanically return the sample to its original shape, is also very high and was measured at > 80%. It should be here mentioned that low twinning stress materials are in generally desirable, however they do not a priori give the highest work output required for actuator materials [3].

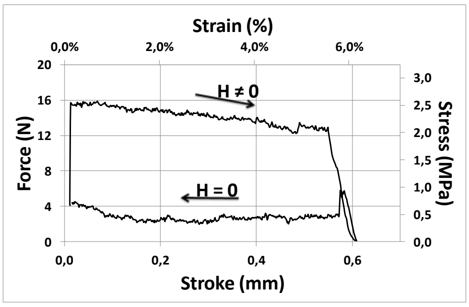



**Fig. 3.** *Stress-strain curve of an MSM element. The magnetic field-induced stress output when applying a field H as a function of the strain, and the stress needed to return the sample to its initial length after removing the field are presented.*

There are two different types of reasoning with respect to the desirable twinning stress. The first being that a crystal with exceptionally low twinning stress might be less advantageous with respect to its magnetomechanical properties, thus resulting in overall less useful work than another crystal with higher twinning stress. The second is within the type of application the crystal is supposed to be used in.

Considering a situation where mechanical work is required in one direction only, it is a well-established solution to introduce a return-spring as a means of returning the actuator to its initial position. Then using an MSM material with minimum twinning stress will result in maximum work during elongation, followed by a minimum difference force required for contraction (i.e. a soft spring only, and minimum loss in work). In this case there also is a well-defined position in power-off condition (viz. contracted).

In other cases it might be desirable to have an actuator that will hold any intermediate position in power-off condition. It is a major advantage of MSM actuators that they can offer such behaviour in a most natural way, as is realized in so-called push-push actuators (see below). In this case, however, the desirable material properties are entirely different. In order to have maximum dwell moment, twinning stress should be just so high, that it is still and safely possible to push one MSM rod using the other. Obviously, twinning stress still must not be more than or even near half the magnetostress in all operating conditions.

In the field of high temperature MSM materials recent progress indicates that NiMnGa compositions demonstrate MFIS at temperatures of up to 71 °C [8]. Here the effect of subsequent thermal-mechanical treatment is of prime importance as recent work demonstrates [8]. Proper training reduced the twinning stress by a factor of two and increased the effective work output of the MSM material by 70 %. Also NiMnGa compositions with transformation temperatures of 90 °C show promising properties with respect to twinning stress after appropriate processing and heat treatment [9].

## MSM Actuators

Actuators driven by MSM materials offer considerable advantages in terms of high stroke combined with fast frequency response, large work output, proportional control, and the possibility to construct compact and long life actuators with minimal tribological problems and overshoot.

These advantages, however, cannot necessarily be used simultaneously in every actuator. Considering high frequency response, it is important to realize that the high frequency response of the MSM stick itself needs to be superimposed with the frequency response of the magnetic circuit. It has been shown that the reaction of MSM to a change in field is essentially limited only by the inertia of the MSM stick itself [10]. Most actuators, however, need to produce the driving field via a conventional coil-and-yoke magnetic circuit. Such circuits have their own frequency response, therefore for the MSM actuator to be faster than, e.g., an electromagnet, additional advantages need to be utilized.

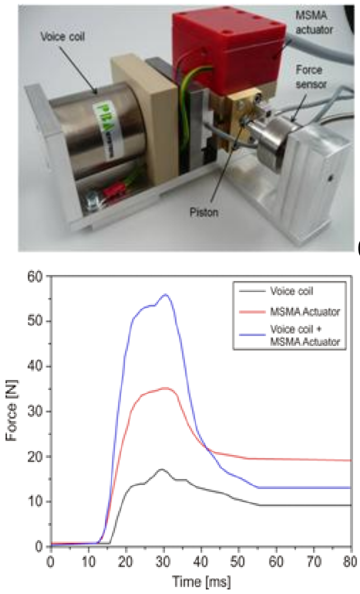
One such advantage may be a close-to-digital field-response of the chosen MSM stick. In this case, the externally useful elongation takes place over a very narrow region of change in magnetic field or current. It has been pointed out before, in the context of magnetostrictive actuators, that such a steep gradient in magnetostrain over driving field can be highly desirable. Technically using such behaviour, however, requires the ability to produce crystals of reproducible, close-to-digital switching behaviour.

It also should be pointed out, that speed in itself is not everything. In principle, and using appropriate driving circuitry, it is possible to build electromagnets with average switching speeds on the order of up to 1 m/s. However, high mechanical loads upon impact on the dead stop become a major challenge then, i.e., the limiting factor ultimately is of mechanical nature, not magnetic. An advantage of MSM is that with their magnetomechanical hysteresis they have a build-in damping capacity.

From this perspective it is a question of fine-tuning the material properties for the desired combination of swiftness and softness.
On a second note, crystals capable of fastest frequency response thus obviously are less amenable for use in proportional switching. For proportional switching it is desirable to have the shape-change distributed over an extended region of change in driving field. This is the antipode of what was stated to be desirable for fast switching. One of the most important messages from these considerations is that when designing MSM actuators, it is necessary to pick the right material for the right kind of actuator. It is not expected to find "the" best MSM material. It is a major advantage of MSM to have a range of intrinsic properties that in principle are adjustable. This allows for a range of different, and attractive technical solutions.
Apart from mechanical fatigue with respect to mechanical loads at the dead stop, with shape-change materials like MSM it is important to consider fatigue in the material itself during actuation. In this field of long life actuation recent results demonstrate the excellent fatigue properties of NiMnGa single crystals. In a recent study 10M single crystal samples were cycled mechanically in uniaxial/tension compression to avoid any surface friction or magnetically induced effects (e.g. eddy current heating) on the structure. The longest test at 250 Hz produced $2x10^9$ cycles without the MSM crystal to break [11]. In another test carried out at ETO MAGNETIC GmbH the NiMnGa single crystal was magneto-mechanically cycled within an MSM actuator at 20 Hz. After 9 months continuous operation and 425 million cycles the test was stopped without the sample to break, however some reduction in the work output was measured [12]. Here it shall be mentioned that the actuator was not optimized for long lifetime, which certainly affected the performance of the MSM element.
Considerable attention has received the so called MSM push-push actuator due to the potential for energy efficient actuation, since the actuator can keep a certain position nearly without energy consumption [13,14]. An example of this type of actuator is shown in Figure 4.


**Fig. 4.** *MSM push-push actuator.*

The MSM push-push actuator is composed of two MSM elements which work antagonistically. When one element elongates in the positive *x* direction, the other one contracts and vice versa. The two MSM elements are excited (or controlled) by two independent magnetic circuits which provide two independently controlled fields along the vertical *y* direction. Instead of two coils it is also possible to use one coil and permanent magnets to further reduce the energy consumption [15]. The displacement is measured on the push rod, and is a measure of the strain of the active elements. Using this type of actuator it is possible to achieve proportional strokes of over 2 mm, depending on actuator design and the active MSM element. It is also possible to hold the push rod at any intermediate position nearly without consuming energy. Also a miniature push-push actuator with the size of $21x21x27\ mm^3$ giving a stroke output of 0,3 mm and a force of 12 N has been reported [15].
In another concept, which claims to utilize the full, up to 2,8 MPa, force output of an MSM material, a so called air-gap free disk spring/MSM actuator has been developed [16]. The high output force of such type of actuator is achieved by the integration of special spring disk combinations with nonlinear characteristics, and a voice coil. Figure 5 shows an example and the force output measurements of this type of hybrid actuator.

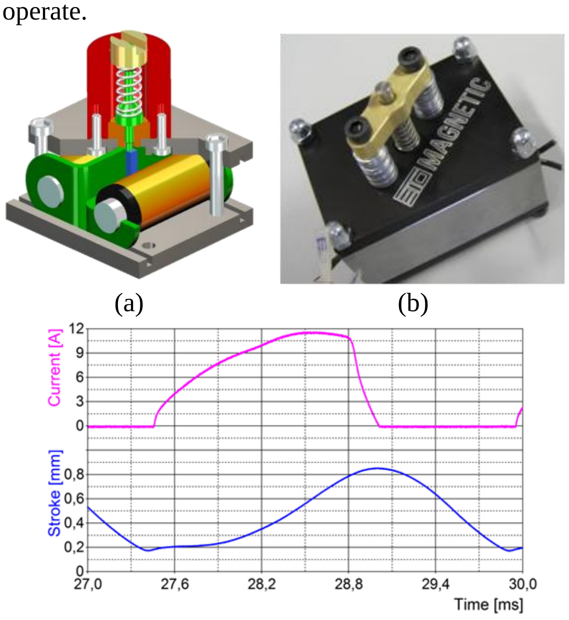


(a)
(b)

**Fig. 5.** *(a) Air-gap free disk spring/MSM actuator, and (b) force output measurements of the actuator.*

In classical spring-type MSM actuators the main target has been to achieve large strokes combined with fast frequency response. In these actuators a spring is used to return the MSM element to its original shape after this has been elongated in the magnetic field. Over the classical electromagnet the MSM actuator demonstrates the possibility to achieve large strokes at high frequencies, as shown for the actuator presented in Figure 6. Here a stroke of almost 0,7 mm is achieved at the frequency of 400 Hz and a response time of 1,6 ms. Taking into account that this is a first prototype device, the results are very promising since these values are difficult to achieve with well-established solenoid solutions. The current can be further reduced, without affecting response time and stroke, when using appropriate current controller. Additional advantages are the reduced friction, due to less magnetomotive forces, and the high fatigue resistance mentioned earlier. A typical electromagnet only in rare cases exceeds 200 million cycles. In another work similarly low response times of 2 ms were measured in MSM actuators [17].

Applications requiring a high positioning resolution are also a field that could benefit by using MSM driven actuators. In a work carried out by Feuchtwanger et al. [18] a nanometric positioning resolution has been demonstrated. The resolution obtained from controlling an MSM actuator in a closed loop with a position sensor is claimed to be comparable to the one obtained with piezo actuator, with the MSM, however, having the advantage of a larger range of motion. Additionally, in the same application the MSM actuator can be used in a "set and forget" mode that would require less power to operate.




(a) (b)

(c)

***Fig. 6:*** *(a) Schematic drawing and (b) MSM spring actuator. (c) Current and stroke measurements of the actuator without current controller.*

In the field of MSM positioning control a lot of work has been carried out also with open loop control, which generally is less expensive. The open loop approach requires an accurate model of the actuator which takes into account among others hysteresis nonlinearities and temperature influences. Mathematical models of hysteresis like the Preisach or the Prandtl-Ishlinskii have been successfully utilized in first MSM applications [19,20]. Also hybrid control strategies have been proposed, where a hysteresis compensator is applied together with a feedback controller to improve the overall performance [21].

In a conceptual design for a novel tripping device for circuit breaker an MSM actuator is utilized due to its fast response. In Figure 7 a schematic drawing of such a device is presented [22]. The modelled design computes an overall tripping time of the system of 0,5 ms and a maximum stroke of 4,3 %.

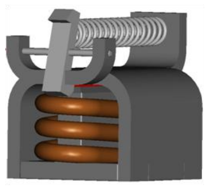


**Fig. 7.** *Design of an MSM circuit breaker.*

MSM actuators have also been reported for application in electro-mechanical transducers used to control pneumatic valves [23]. Here the MSM element can be utilized to control pneumatic elements such as direct-action proportional throttle valves or pilot valves. Besides shorter opening and closing times, improved dynamic properties and better resistance to external vibrations contribute to improved performance of the MSM solution.

Significant effort has also been given in developing modelling and simulation tools for optimizing MSM actuator design. The magnetic simulation of the MSM material started already at the early development stages of this new technology [24]. More recently magnetostatic finite element methods have been proposed, which are also compatible with the requirements of product engineering processes in automotive and other industries [25]. Here, the dynamic anisotropic magnetization of the MSM material is taken into account, as well as the fact that, opposite to conventional reluctance actuators, magnetic flux and force directions are typically aligned perpendicular.

**MSM Sensors and Energy Harvesters**

The inverse MSM effect has been used for sensor and power generation applications. The first pioneering work on the topic has been carried out some time ago by one of the authors [26]. In a very interesting approach the actuator and sensor effects have been used in an MSM device with proportional position control and self-sensing capability. The position feedback in the actuator is based on resistance change and measurements on the MSM element in response to its elongation [27].

In a similar mechanical sensing approach it has been shown that although the stress-strain response for uniaxial stress on an MSM element is nonlinear and shows a hysteresis the dependence of the magnetic flux density in the vicinity of the sample is linear [28]. In a prototype of a displacement sensor the change of the signal from a GMR sensor attached close to the MSM element was monitored during mechanical elongation. The result is presented in Figure 8 and demonstrates that the signal is proportional to the MSM element displacement. The small hysteresis observed can be eliminated by carefully selecting the flux density of the external field generated by small permanent magnets.

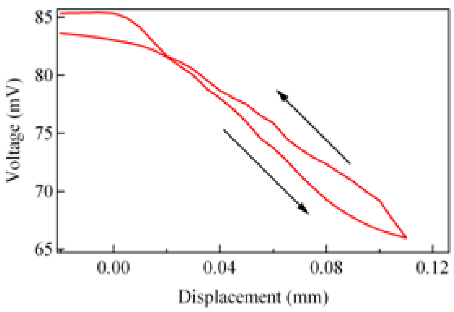



**Fig. 8**. *Measured signal of an external sensor during elongation of an MSM element.*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