Magneto-Mechanical Energy Conversion in Magnetic Shape Memory Alloys

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Abstract. Magnetic Shape Memory (MSM) alloys present a novel means of transforming electric energy into mechanical work via the intermediate generation of magnetic field from electric current. They thereby follow a similar path of energy conversion as classical electromagnets. In this paper we will compare known designs of MSM actuators and electromagnets and discuss their characteristics based on properties of available MSM materials.

1. Introduction
Solid state actuators are materials that exhibit a noticable macroscopic shape-change upon application of a driving field, which e.g. could be electric, magnetic or thermal. Significant effects are seen and technically utilized in piezoelectrics (with electric field as driving field) and in (Giant) Magnetostrictive Materials (GMM, with magnetic field as driving field). In both cases strains on the order of 1,000...2,000 ppm are possible. On the other hand, there is a class of materials called (thermal) Shape Memory Alloys (SMA) that upon thermal cycling show shape-changes of several percent. In Fig. 1 the general idea is depicted. From a high-symmetric high-temperature phase the material transforms into a lower-symmetry low-temperature phase. There are different possible orientations to realize this reduced symmetry (in this two-dimensional sketch there are two), depicted as light and dark grey variants. Chosing the same variant over the entire sample would result in macroscopic shape-change, which normally will not be a preferred solution. Instead, macroscopic shape will be preserved by having different sections (twins) of the crystal transforming into different variants. These sections meet at twin boundaries that will be slightly off 45°, depending on the disparity between the tetragonal axes. These twin boundaries in principle are mobile, i.e., the sample may be significantly deformed without actually destroying the crystal structure anywhere — the sample simply accommodates such deformation by moving twin boundaries. Upon warming up into the high-temperature phase, however, this freedom in macroscopic shape disappears, since the cubic lattice does not allow for any of this. As a result, and with significant driving force, the crystal regains its “memorized” shape. So in this solid state active material high strains are combined with high stresses, however, since it depends on a phase transition, it is strongly dependent on environmental parameters (temperature). Also, it inherently is somewhat slow in the direction of cooling down.

Magnetic Shape Memory (MSM) alloys are named in some analogy to SMA, however, this resemblance in name is somewhat misleading. MSM work in the low-temperature, twinned phase only, so there really is no shape memory upon re-entering some high-symmetry high-temperature phase used in this effect (although these materials may also be used as thermal...
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Figure 1. Schematic of thermal SMA. Top: cubic high-temperature phase. Bottom: tetragonal low-temperature phase, left to right: first twin; twin boundary; second twin.

Figure 2. Schematic of MSM. Top: without external field. Bottom: with external field. Left to right: starting from easy axis variant; twinned state; hard axis variant.

SMAs). The driving force in this case is magnetic. In a ferromagnetic martensite with a pronounced disparity between magnetically hard and easy axes, magnetic field will provide a driving force favouring one variant over the other. In order for this to show some noticeable effect, the twin boundaries need to be soft enough so the magnetically induced force will be sufficient to move them. This MSM effect is depicted in Fig. 2. Considering (top panel) the two variants by themselves, either will have a magnetically preferred axis (easy axis) and the moments will be oriented accordingly (arrows). When applying an external magnetic field (bottom panel), the effect will be as depicted. Starting from a sample that is oriented with the easy axis along the external field direction, nothing will happen (left). With a sample in a twinned state, the first reaction of the magnetic moments in the unfavourable twins will be to slightly rotate towards the direction of external magnetic field, which would constitute the “normal” magnetostrictive effect. In MSM alloys, however, there is an even more efficient reaction to external field, viz. twins of magnetically favourable orientation will grow (center), and at the same time the sample will macroscopically change its dimensions. With a sample starting from a single-variant state oriented along the hard axis, soft-axis twins will form and grow, as mentioned before (right). This effect is rather interesting, as it combines the strains of SMA (several percent) with the magnetic driving field of magnetostrictive actuators, thus it would seem it gives best of both worlds. There is one caveat, though, viz. that energy does not come for free, and of course an actuator having one or two orders of magnitude higher strain than GMMs will also have significantly less magnetic-field induced stress.

2. MSM Actuator Geometries

Still MSM alloys continue to receive much attention from physicists, material scientists and engineers alike, and the reason for this is that MSM alloys combine a number of properties that makes working with them challenging, but also promise interesting new applications provided its various properties can be used advantageously. Considering MSM as the basis for an actuator, first the different possible modes of operation need to be considered (see also [1]).

Twin boundary motion and thus macroscopic shape-change may be introduced either magnetically or mechanically as is depicted in Fig. 3. Assuming the magnetically preferred axis to be the short axis (as is the case in the most-studied class of alloys, Ni$_2$MnGa), elongation may be induced by either transverse field or transverse compressive stress, while contraction may be induced by either axial field or axial compressive stress. In order to build a useful actuator, at
least one of the two, elongation and compression, should be driven by an intelligent signal, which in most cases will mean that at least one shape-change should be induced by an electromagnet. The latter may, e.g., be induced by yet another electromagnet, or by a mechanical return spring. The latter became a kind of standard solution, however, quite a number of different designs have been proposed to the present day (see, e.g., [2] for an overview).

Another design choice that needs to be made when using a single electromagnet and a return spring (which, again, is not necessarily the case, there are alternative options) is wheter to close the magnetic circuit such that induced mechanical deformation is in the plane of the magnetic circuit, or perpendicular to this plane. In Fig. 4 the option of induced deformation (vertical) perpendicular to the plane of the magnetic circuit is shown. To the left, the most simple conceivable circuit is shown, while in practical applications typically a design closer to the right panel sketch of Fig. 4 will be chosen. In this design, very high field strength at the position of the MSM element can be achieved, while simultaneously stray-flux is efficiently minimized. In this design almost the full actuator height might be used for MSM active material, thus very high strains (in relation to actuator dimension) are possible. This geometry has become a kind of standard design described in various publications (see, e.g., [3]).

Alternatively, the direction of induced mechanical deformation can be within the plane of the magnetic circuit, i.e., the field lines do not close laterally around the MSM element, but under it. This geometry, and its evolution from the design previously described in Fig. 4, is shown in the left three panels of Fig. 5. In the right panel of Fig. 5 this design is rotated such that it results in a very compact design described in [4] (deviant from full rotational symmetry, an MSM circular ring obviously needs to be substituted by a polygon of MSM platelets). This design has a few shortcomings, e.g., having a number of MSM elements in a single magnetic

**Figure 3.** Schematic of operational modes in MSM actuators. Top: magnetic field induced shape change. Bottom: mechanically induced shape change. Left: elongation. Right: contraction.

**Figure 4.** Schematic of a standard actuator design with magnetic field in xy-plane. MSM in blue, yoke in grey, coil in yellow.
Figure 5. Schematic of an actuator design with magnetic field in xz-plane and its development into a rotational symmetric geometry.

circuit which will lead to problems if these elements are not rather similar in their properties. Furthermore, strain in relation to actuator height is significantly reduced, as only a fraction of the total actuator height is used for MSM elements. On the other hand, significantly higher forces (stresses in relation to the full actuator cross-section) theoretically are feasible with this design as compared to designs similar to the ones shown in Fig. 4.

3. Comparison of Actuator Principles

One fact has been hinted at a few times now, viz. that it is not sufficient to compare MSM (or any solid state actuator) to any another actuator principle by just comparing material properties. The reason for this is that solid state actuators in most cases are not operational by just taking a piece of active material. For one thing, they require their driving field, and if this, as with MSM, happens to be a magnetic field, this field cannot be supplied by sticking a wire into the MSM element; it needs to be generated at the location of the actuator, meaning there needs to be a yoke, a coil, connectors, fixtures, a return spring, housing etc., a lot of things that just take up space. A lot of space. The actual volume fraction of course varies depending on design, but it is realistic to think in terms of a few percent of actuator volume for actual MSM active material. This is not quite as bad as it sounds — it just means that by focusing on the material properties of the MSM material in order to compare it with other (solid state) actuators, one is prone to neglect what is actually the majority of volume and weight required in any prospective application.

Another fact that must not be forgotten is that the ultimate benchmark is neither GMM, piezoelectrics or SMA, but electromagnets. There are areas, where GMM and piezoelectrics, as well as SMA have their ideal applications, but the majority of small-stroke linear motion that is technically induced in this world is induced either electromagnetically, by pneumatics or by hydraulics. And as for the latter two, somewhat down the line there will be an electromagnet, e.g., in a pilot valve. Specifically with MSM, realistic strokes and forces (in actuator geometries realized so far) compare rather favourably with what is usually done by electromagnets. Note that this is different for, e.g., piezoelectrics — they provide a range of high stresses and low strains at very high precision that is hard to do in any other way. For MSM however, electromagnets are an obvious benchmark. An MSM actuator will need everything an electromagnet needs to generate its driving field, plus the MSM elements (introducing additional costs and complications). So there needs to be a significant advantage to render MSM an interesting alternative. In this paper we want to demonstrate, how an actuator comparison might look like, in order to give some indication, whether MSM as a solid state actuator compares at all favourably to an established, simple solution like an electromagnet.
4. A Direct Comparison between an MSM Actuator and an Electromagnet

It was pointed out above that a direct comparison of a solid state actuator and an electromagnet is not possible based on material properties of the active component alone. On the other hand, comparing these two actuator principles based on any arbitrary choice of design and technical requirements runs the risk of creating the impression of an absolute comparison of the two actuator principles. This it inherently cannot be. Keeping this in mind, we believe it is still instructive to go for such a direct comparison based on arbitrary, but meaningful assumptions of technical requirements.

In order to keep the geometries easily comparable, we will within a cylindrical volume consider the general actuator designs illustrated in Fig. 6. In the left panel, a closed magnetic circuit is shown (that obviously will not do any useful work). In the center panel, this same circuit is opened such that there is a working air gap that will exert a downwards force on the armature (electromagnet / pot magnet). The air gap volume indicated in blue is the nearest equivalent to the active element in a solid state actuator. The work done is limited by the electromagnetic energy stored in the opened air gap, which in turn is reasonably limited mostly by realistic working points of the yoke material. The air gap does not really impose any other limit. In the right panel, this same general magnetic circuit is opened such that MSM elements may be introduced. Note that the major reason to chose a design similar to that in [4] is that this allows for a close analogy between these circuits. The active volume here of course are the MSM elements. In contrast to free air, they do impose their own limitations. Their maximum work is limited by the difference between hard- and soft-axis magnetization, any further field applied will not result in useful work. As typical MSM saturation polarizations are significantly lower than those of typical yoke materials, the work per active volume is much lower than in the case of the electromagnet and its air gap. On the other hand, of course, its permeability is much higher, so one can assume to have the chance to introduce significantly more active volume. It is the major aim of this paper to illustrate how these different tendencies in principle interact.

This comparison aims at MSM and electromagnets as a means of producing a maximum of mechanical work from a given amount of electric energy in a given volume. This is a first important assumption — this needs not to be the case, there are applications with a different focus, and this comparison is not applicable for such applications.

The volume we will allow ourselves is a cylinder of one inch in diameter and one inch in height, and we will require ten mil in stroke (i.e. 1% of strain in relation to the overall external dimension of the actuator). This last assumption is not entirely random, obviously. A 5M martensite Ni\textsubscript{2}MnGa will at most produce about 6% strain. Due to the assumed MSM actuator geometry, only a reasonable fraction of the height can be used for active material, so it appears most reasonable to require only about the above quoted stroke. Twice that might be conceivable without leaving this design concept, but probably not much more than that). It will be the aim of this comparison to meet this requirement and simultaneously provide as much force as possible at the beginning of the motion.

Figure 6. Schematic of a closed magnetic circuit (left) and its development into an electromagnet (center) and an MSM actuator (right) for direct comparison.
The mechanical requirements thus being fixed, the amount of allowable input electric energy needs to be fixed — we choose 10 W of input power, $P$, and again this choice is not entirely random. It is adjusted such that it results in reasonable current densities in both actuators and in Joule losses that are conceivable to accept in an application for more than infrequent use at the given volume. This choice has significant influence on the outcome of the comparison, as it determines the advantageous volume fractions of copper and iron.

In first approximation, it is instructive to consider the magnetic circuit to be a single, closed loop without any stray-flux. This of course is a very significant simplification, but specifically with the rather short lengths of free space in the considered magnetic circuits and the moderate input power, one might argue that it is not expected that these circuits will suffer to much from stray-flux. This assumption very much simplifies analytical modelling and such facilitates an understanding of the circuit. This procedure is specifically instructive in the case of the MSM actuator, as in this simple model it is rather straightforward to keep track of the quantities that will determine the realistic output power. Under these assumptions, the magnetic behaviour can be derived from

$$\Theta = \Phi \sum_i R_{m,i}(\mu_r(B))$$

where the $\Theta$ is the total magnetomotive force (amp turns) driving the system. $\Phi$ is the magnetic flux induced in the circuit and the $R_{m,i}$ are the reluctances for the various parts of the circuit that may be calculated based on knowledge of their permeabilities $\mu_r(B)$ in their respective working points (that in turn follow from geometry and $\Phi$). This equation is easily solved self-consistently.

For any such modelling, assumptions about the induction curves for the involved magnetic materials need to be made (i.e., about $\mu_r(B)$). For the yoke, we will consider a standard free cutting steel, 11SMn30, in annealed condition. This may be regarded as a good compromise between expense and magnetic properties. A representative curve $\mu_r(B)$ is shown in Fig. 7 (left panel). For MSM, we assume Ni$_2$MnGa as reportet in [4], somewhat simplified and reduced to a permeability for the hard axis of 2.0 up to a saturation polarization of 0.7 T, and a permeability for the soft axis of 210 up to an identical saturation polarization of 0.7 T. This results in the curves $\mu_r(B)$ shown in Fig. 8 (left panel). Note that the circuit will have to be designed such that it will provide rather high fields in the MSM material. At such working points, the initial or maximum permeability at very low fields really is not of much consequence, since the relevant reluctances are defined by the permeabilities at the respective working points. So by simplifying the induction curve as described above, little harm is done.

Finally, a few assumptions about the coil need to be made. We will assume a Cu filling factor, $\eta_{Cu}$, of 60%, which is easily feasible, and we will further assume that there is a radial gap of twice 0.5 mm between iron and copper, and a total axial gap of 2.0 mm (used up by the
bobbin of the coil, electrical connections etc.). We will consider the power consumption based on resistive losses alone at 50°C, i.e. at $\rho_{el} = 0.02 \, \mu\Omega\text{m}$ of resistivity. Total magnetomotive force then may easily be computed from

$$\Theta = \sqrt{P \eta \rho_{el} h (r_o - r_i) \over \pi (r_o + r_i)}$$

where $r_i$ and $r_o$ are the inner and outer radii of the coil, respectively, and $h$ is its height. $r_i$ and $r_o$ are free parameters in the optimization, $h$ is determined by the required stroke. It is assumed that 6% of stroke are actually available for external work, which for real materials is not doable. It still may give an impression of an upper limit for possible MSM actuator performance.

Assuming the MSM actuator geometry described above, in optimizing there are two additional parameters, viz. the radii $m_i$ and $m_o$, which denote the inner and outer radius of the MSM element, respectively. Increasing $m_i$ shifts the MSM elements outside, thus increasing the used circumference and active cross section and force at constant width $m_o - m_i$ of the MSM element, however, it also increases the volume that needs to be filled with sufficient magnetic field. So here it is rather useful to have this excessively simple model, as it allows to quickly check various options. This model of course does not directly result in an output force. The force is deduced from magnetic field in the MSM element(s) by

$$F = A \int_0^{H_0} (B_{soft}(H) - B_{hard}(H)) dH$$

where $A$ is the active cross section of the MSM element(s)

$$A = \pi (m_o^2 - m_i^2)$$

Obviously, this assumes an MSM crystal of rotational symmetry, which is impractical (though it would be neat in many respects). In reality, as was pointed out above, this ring would have to be approximated by a polygon of MSM crystals, as was described in [4]. There are specific challenges with this design, that were mentioned in the given reference. These technical problems, however, do not lessen the value of this design for the present consideration of MSM in direct comparison with an electromagnet. Here, it is rather a question of possible work per actuator volume; it is not primarily a question of optimum basic geometry.

It is further worth noting that the optimum of this design will not only depend on the curves $\mu_r(B)$ for all the involved materials in the reluctance circuit, but also on the assumed twinning
stress. The reason for this is the non-linear shape of the curve \( F(H) \) as depicted in Fig. 8 (right panel). The most force per field is realized at low working points, so for zero twinning stress the best design choice would be to keep the iron close to maximum permeability (so a minimum of reluctance is contributed by the yoke) and maximize MSM cross-section, i.e., use a low, but efficient working point and lots of active surface area (low stress and large area). With high twinning stress, however, it is crucial to have a large ratio of total magnetic stress and twinning stress, i.e., the working point needs to be higher, which usually will mean that the active surface area of MSM will be smaller (high stress and small area). Here, two examples will be considered.

Zero twinning stress (to check which treasures may wait at the end of the rainbow) and 0.5 MPa of twinning stress, representing a realistic or even somewhat pessimistic value.

First we will consider zero twinning stress. The optimization will be done for soft-axis behaviour, i.e., for maximum force in the elongated state. As a result, one finds a suitable design with a force of 182 N at a working point of 91 kA/m. 62% of the total reluctance are then contributed by the MSM element(s), 22% by the air gap due to radial contraction of the MSM element(s) by 6% and just the remaining 16% are contributed by the yoke, i.e., the vast majority of magnetomotive force is indeed invested in the MSM effect. Note that even at this very low working point, the relative permeability of the assumed MSM material is a mere 7.1, compared to the assumed yoke material that in all elements that constitute the circuit is between 300 and 2,500. This disparity of course is the reason why it is possible to have such a large fraction of magnetomotive force useful for the MSM effect.

It is interesting to also consider the case of hard-axis behaviour for this geometry. In that case, the force increases to 294 N. It may come as a surprise that in hard-axis condition (contracted), with a relative permeability of only 2.0, the effective useful force is even higher than in soft-axis condition (elongated), where the relative permeability of the MSM element(s) was higher, viz. 7.1. The reason for this is twofold. First, the air-gap resulting from the shape-change is not present in this case, so the magnetomotive force expended on this in case of the elongated geometry is safed for better use. Second, it turns out that by increasing the reluctance of the MSM element(s), the yoke is forced into a more favorable working point (closer to maximum permeability), so effectively 98% of the total reluctance is contributed by the MSM element(s) in this condition. This second argument obviously is somewhat of a coincidence with the material properties chosen for the yoke in this example.

As advertized above, we want to consider a second example, viz. an MSM material of identical \( \mu_r(B) \), yet with a finite twinning stress of 0.5 MPa. In the process of optimizing the assumed simplified circuit for these conditions, this just means that the effective force needs to be reduced by twice the twinning stress (once for overcoming the twinning stress in the first place and once for additionally overcoming the return spring, which at least needs to equate to the twinning stress). Also, it becomes desirable after optimizing the circuit under the assumption of soft-axis magnetic behaviour to check whether the field, assuming hard-axis magnetic behaviour, will be sufficient to induce twin-boundary motion in the first place. For the design discussed above this would not be the case. That actuator would not be able to do any useful work assuming a twinning stress of 0.5 MPa (effective externally available force is negative).

After re-optimizing the geometry for 0.5 MPa of twinning stress, the useful force for external work calculated in soft-axis conditions (elongated) is severely reduced to just 76 N, with a length of MSM in the circuit (=thickness of MSM platelets in polygon) of 1.7 mm only (less then half of the optimum at zero twinning stress, viz. 4.0 mm). The working point is increased to 226 kA/m, 67% of the magnetomotive force is used up in the MSM element(s) and 13% in the air gap resulting from the elongation. The effective relative permeability in the MSM element(s) in this case is 3.5 only. Again the useful force is increased in hard-axis condition as compared to soft-axis condition, in this case to 122 N. This confirms that there would not be a problem to induce motion in this actuator design.
Figure 9. FEM analysis of the discussed actuator geometries. Left to right: Zero twinning stress MSM actuator, soft- and hard-axis condition; 0.5 MPa twinning stress MSM actuator, soft- and hard-axis condition; electromagnet, opened and closed armature condition.

For all four cases, zero twinning stress and 0.5 MPa twinning stress in soft- and hard-axis behaviour each, Finite Element Method (FEM) calculations were done to give some impression of the amount of stray-flux that is to be expected in these circuits (see Fig. 9, all calculations done using ANSYS/Ansoft Maxwell). A few remarks may be made. First, it is rather surprising that the bottom part of the magnetic circuit for the MSM actuators is as thick as it came out in the optimization. It certainly is rather over-dimensioned when comparing its working point to the the working points of the other parts of the yoke. So there would have been space to introduce more magnetomotive force by adding Cu into these circuits without any problem. Still, from the optimization this does not turn out to be desirable, since that would mean the working point would shift to higher induction, the permeability of the yoke would be decreased, a higher fraction of the total magnetomotive force would be invested in the yoke and effectively, less useful force would be generated in the MSM element(s). This again is due to this specific choice of yoke material and cannot be expected to be the case in every possible actuator design. Since in the case of MSM the force is driven by the field in the MSM element(s) (while its induction remains significantly lower than the yoke’s anyway) it might, however, be expected to be a general tendency to best run the yoke close to its highest permeability so most reluctance is in the MSM. Furthermore, from these calculations it can be seen that with hard-axis behaviour (in the contracted state) there will be noticeable stray-flux over the coil, so it is to be expected that the calculated increase in force in this state will not be realized in reality and would at least partly vanish using a slightly more elaborate model.

Finally getting to the comparison with the electromagnet, a similar optimization is done, however, in this case without the detour over the circuit model. This design is easily optimized in FEM directly, so it is not really necessary to look at a simplified circuit model. The results are shown along in Fig. 9. In this case, there is noticable stray-flux when the armature is opened, while there is none, when it is closed (as it should be). Note that since in closed condition the full circuit consists of 11SMn30, the working point becomes rather high, and accordingly the force increases significantly to 365 N. The appropriate comparison, however, is the opened-armature condition, and in this case, 132 N are possible.

In order to facilitate direct comparison, all these resulting forces over stroke are shown in a joint Fig. 10. For the electromagnet the full curve force vs. stroke was calculated (FEM results shown), for the MSM actuators only the forces at the initial and final state are reported (circuit model results shown). Filled symbols are zero twinning stress, open symbols are 0.5 MPa twinning stress. It is interesting to note that (even though the dashed line is really at most a guide to the eye) for zero twinning stress (i.e., ideal energy conversion, as is the case or the air
gap of the electromagnet), the advantage that is with the MSM actuator at the initial state is with the electromagnet at the final state. At this point it should be mentioned that there is an important difference in that the MSM actuator by nature pushes away from the magnetic circuit, while the electromagnet pulls into the circuit, i.e., the forces both shown as positive here really are of opposite direction — this can easily be fixed by appropriate design measures and does not really influence this comparison. It means, however, that for the MSM actuator the initial position is at zero stroke, while for the electromagnet it is at 10 mil (0.254 mm). This means, the electromagnet starts at its lowest force and will show increasing force over stroke, while the MSM actuator will start at highest force and show decreasing force over stroke. Again, keep in mind that this increase of force in hard-axis conditions is somewhat of an artifact of the omission of stray flux terms, still, even if the force would be constant and equal to the force in soft-axis conditions, this might in certain applications be regarded as advantageous.

5. Conclusion
In this paper we used an assumed set of technical requirements to directly compare MSM solid state actuators with conventional electromagnets. The assumed goal was producing maximum mechanical work at a given stroke, input power and actuator volume. All results need to be treated with applicable care — they are dependent on these assumptions. In the presently studied case it turns out that the feasible work is rather comparable assuming zero twinning stress for the MSM. However, it becomes notably reduced if 0.5 MPa twinning stress is assumed. To our understanding this means that MSM actuators might be expected to be most competitive in areas that do not focus solely on their capability to transform magnetic field energy into work. It will be crucial to make use of all their properties, including finite twinning stress (and, e.g., concurrent damping properties). Even though MSM might come close to the properties of well-known, cheap electromagnets, or even surpass them in certain points, it needs to be kept in mind that there might be expected to be a tremendous reluctance to use such a novel actuator principle in a first technical application. This reluctance is best overcome by offering a qualitatively new behaviour. Considering the amount of interesting properties MSM have shown so far, it appears realistic to find such a qualitatively new and promising application.

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