REVIEW OF NI-MN-GA HEUSLER ALLOY: PROPERTIES AND APPLICATIONS OF ACTUATORS WITH MAGNETIC SHAPE MEMORY

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Abstract. Heusler alloys are known as suitable candidates for many applications due to their unique and tunable electronic structure, which influences the peculiar physical properties ranging from superconductivity, magnetocaloric, thermoelectric and magnetic shape memory effect. Alloys of the Ni-Mn-Ga family have attracted much attention for research since the early years, as it is one of the leading examples of Heusler material. Magnetic Shape Memory Alloys (MSMA) show high potential as an emerging class of smart materials that can function as both actuators and sensors for a new generation of simple and fast digital components that produce high mechanical performance in a limited space enabling the obtaining light and compact miniaturized actuators combined with cost reduction. Several areas of research focus on the development of magnetic shape memory alloys: alloy manufacturing methods, definition of properties and applications. In this context, this article presents the types of magnetic shape memory actuators reported in academic research, as well as the structural, thermal and magnetic properties of Ni-Mn-Ga alloys.

Keywords: Heusler alloy, Ni-Mn-Ga, MSMA, Magnetic shape memory alloy.

1. INTRODUCTION

In the field of micromechatronics and microrobotics, active materials are generally the most commonly used due to their high resolution and potential for distributed actuation. Based on this premise, magnetic shape memory alloys (MSMA) are attractive active materials because they exhibit significant deformation, reaching values on the order of 10%, similar to conventional shape memory alloys (SMAs), but with the ability to provide a response time up to 100 times faster than SMAs (Gauthier et al., 2006).

The magnetic shape memory effect (MSME) is the most well-known functionalities of Heusler compounds. Large deformations in these alloys are achieved through the reorientation of martensitic variants, where twin boundaries are highly mobile. This reorientation can be induced by stress and/or magnetic field. The complex behavior exhibited by these materials is primarily a result of the strong coupling between magnetism and the structure, driven by the martensitic transition (Acet et al., 2011; Maji, 2017; Ullakko et al., 2001).

The Ni-Mn-Ga system is one of the most extensively studied materials with magnetic shape memory. The magnetic field-induced deformation in this alloy was first experimentally observed by Ullakko et al. (1996), who reported a magnetic field-induced strain (MFIS) of 0.2% in a single-crystal Ni_2MnGa alloy. It is possible to achieve large reversible deformations induced by a magnetic field when the crystallographic domains (twin variants) of the martensitic phase reorganize in response to the stress induced by the magnetic field. A refined understanding of the microstructure and crystal structure associated with the austenite-to-martensite transformation is crucial as the properties of Ni-Mn-Ga alloys are highly sensitive to compositional changes (Zhou et al., 2017).

What sets magnetic shape memory alloys apart from conventional shape memory alloys and makes them unique among any other material is that the microstructure of the martensite can be manipulated when exposed to a magnetic field. This can result in significant macroscopic deformations induced solely by the magnetic field. Furthermore, these changes can be "remembered" by the microstructure of the martensite. With the discovery of this large deformation, Heusler alloys have made a significant impact on research, almost a century after their initial discovery, advancing the development of magnetic field-driven actuators (Acet et al., 2011).

In this context, this article presents the properties of the alloys of the Ni-Mn-Ga family. In the following, the basics of MSMA actuator design are introduced briefly. Subsequently, three concepts for linear actuators driven by MSMA will be presented. These concepts are the spring/MSMA, the push–push, and the push–pull concept. The article only focuses on MSMA actuators driven by an external magnetic field, and other applications have been disregarded in this review.

2. PROPERTIES OF THE NI-MN-GA TERNARY ALLOY: DESIGN OF ACTUATORS WITH MAGNETIC SHAPE MEMORY

Among Heusler alloys, Ni-Mn-Ga alloys have garnered significant research attention since their early years, as they represent a prominent example of magnetic shape memory materials. Early research on the shape memory phenomenon, magnetic and thermal properties, as well as martensitic transformations of the Ni-Mn-Ga alloy, were reported by Chernenko et al. (1995a), (1995b), and Chernenko et al. (1994). However, the magnetic field-induced deformation in this alloy was first experimentally observed by Ullakko et al. in 1996, who reported a deformation of 0.2% in a single-crystal Ni_2MnGa with a magnetic field of 0.8 T applied at 265 K. It is possible to achieve large reversible deformations induced by a magnetic field when the crystallographic domains of the martensitic phase reorganize in response to the magnetic field-induced deformation.

At room temperature, Ni-Mn-Ga alloys can exhibit one or two phases: the Austenitic phase and/or the Martensitic phase. Figure 1 illustrates the specific crystal structure of each phase. The phase with a high-symmetry cubic structure is stable only at high temperatures and has only one variant, known as the Austenitic phase. On the other hand, the phase with a tetragonal or hexagonal structure is referred to as Martensitic and presents multiple variants. The crystal structure of the martensite is dependent on the alloy's composition. In stoichiometric Ni_2MnGa, the martensitic phase has a modulated five-layered (10 M) structure. As the composition deviates from stoichiometry, the austenite phase first transforms directly into a seven-layered (14 M) martensite, and finally into a non-modulated (NM) tetragonal phase (Straka et al., 2008).
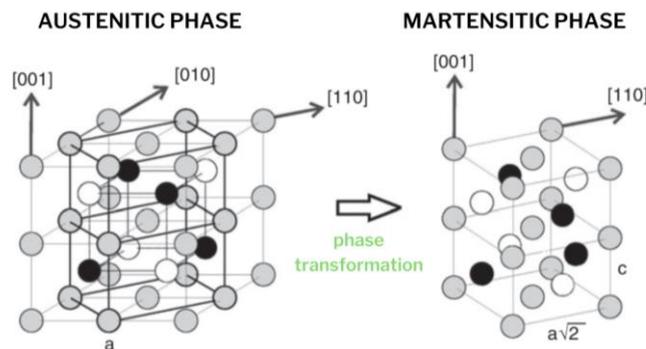

Figure 1. At room temperature, Ni-Mn-Ga alloys can exhibit different phases, depending on the specific composition of the alloy.

The phase transformation, especially the martensitic phase, has a significant influence on the properties of Ni-Mn-Ga alloy family, both structurally and magnetically, and it is the origin of the traditional and magnetic shape memory effect. It is in this low-temperature phase that the properties are strongly influenced by magnetic fields. Since the martensitic transformation temperature is composition-sensitive, Ni-Mn-Ga alloys with compositions deviating from stoichiometry are commonly used to stabilize the martensitic phase at room temperature.

The chemical composition of the ternary Ni-Mn-Ga alloy is identified as the primary factor by authors such as Ullakko et al. (2001), Rani et al. (2012), Khan et al. (2018), Laitinen et al. (2021), and Natalia et al. (2021) that influences crucial properties, including martensitic and magnetic transformations, phase transition temperatures, crystal structures, saturation magnetization, and consequently, magnetostructural effects. The amount of each element, represented by x, y, and z, in the ternary alloy $Ni_xMn_yGa_z$ describes the structural and magnetic changes.

Extensive studies have been performed on the composition dependency of martensitic transformation temperature. Due to the different material processing methods and heat-treatments, the results from different groups are not fully consistent. The results plotted in Figure 2 are particularly selected from the literature in order to include three typical substitutions (Ni substitution for Mn, Ni substitution for Ga, and Mn substitution for Ga). The composition is mapped into number of valence electrons per atom, e/a, which is a widely used parameter for classifying the concentration dependence of the martensitic transformation temperature. The Figure 2 shows that the martensitic transformation temperature increases with increasing e/a, and Curie temeprature (Tc) keeps rather constant at about 370 K when the composition is close to stoichiometric. However when composition is further deviated from the stoichiometry, the Tc will decrease with increased electron concentration (Aaltio et al., 2016).
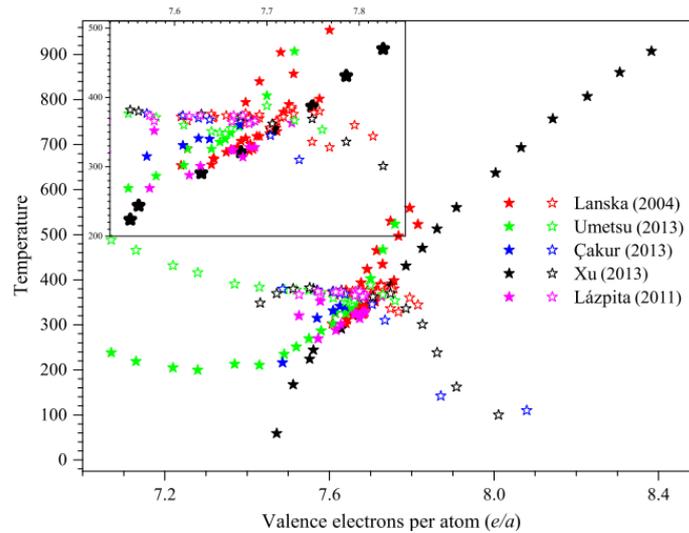
Figure 2. The composition dependency of martensitic transformation temperature and the Curie temperature in K. The solid symbols are for martensitic transformation and open symbols Curie temperature. The inset shows the data points at the intersection of Curie temperature and martensitic transformation.
(Aaltio et al., 2016)

Results reported by Jiang et al. (2003) demonstrate that, in general, an excess of nickel stabilizes the martensitic structure, leading to the appearance of martensite at room temperature with a nickel content above 52%, meanwhile, Ni_2MnGa exhibits a cubic austenitic structure. It was also found that the substitution of nickel with gallium is more effective in stabilizing the martensitic structure. Sokolovskaya et al. (2021), based on computational theoretical data, reported the same conclusion that the cubic austenite has its stability region close to stoichiometric Ni_2MnGa, while the tetragonal martensite exhibits stability over a wider range of manganese and nickel compositions.

Martensites, including non-modulated (NM), ten-layered modulated (10M), and fourteen-layered modulated (14M) martensite, contain twin boundaries that can or cannot be moved under an applied magnetic field. The growth of a twin boundary is responsible for the magnetic field-induced strain. Among the MSMAs, Ni-Mn-Ga with a 10M structure is the most extensively studied MSMA, mainly because it has relatively low twinning stress and high work output, while maintaining a large MFIS. Therefore, most existing applications and devices based on MSMAs use alloy compositions that exhibit this crystalline phase (Toman et al., 2018; Kulagin et al., 2022).

The macroscopically observable strain induced in MSMA is caused by the micro-structural rearrangement of martensitic variants. Since the crystallographic variants of martensite have different preferred magnetization directions, applied magnetic fields can be used to select certain variants over others, resulting in the macroscopic shape change. The constitutive response is nonlinear and hysteretic, which gives the material interesting characteristics in terms of possible applications. Each of the martensitic variants are magnetized along a preferred crystallographic direction, named the magnetic easy axis (M^{sat}), which in this case is aligned with the short edge "c" of the tetragonal unit cell, where it must be understood that the magnetization of a single unit cell is an idealized concept, Figure 3(a). The magnetization can be oriented in either the positive of negative easy axis direction. With this configuration of orthogonal preferred directions of magnetization, it is evident that the application of an external magnetic field can be used to favor selected variants over others, since an alignment of the magnetization and the magnetic field inside a magnetic material is energetically desirable. In the context of MSMA this process is referred to as the magnetic field-induced reorientation of martensitic variants, which is the microstructural mechanism causing the macroscopic magnetic shape memory effect (Kiefer and Lagoudas, 2005).

In research reported by Sozinov et al., (2002), it is observed that there is a strong uniaxial anisotropy in the martensitic variants and that the easy magnetization (M/M_S) axis corresponds to the "c" axis of the variants, Figure 3(b). The magnetization is considered fixed to the easy magnetic axis of each martensitic variant due to the high magnetic anisotropy. Martensite variants that have their easy axis along the direction of the applied field grow at the expense of other variants by twinning motion driven by the applied field.

Figure 4 summarizes the behavior of Ni-Mn-Ga under temperature, mechanical and magnetic actions. At high temperature, the MSMA is in austenite crystallographic phase. When the sample is cooled, three martensite variants (M1, M2 and M3) appear. The M1 variant presents a short axis and an easy magnetization axis in the y direction. For a xy plane motion, the M3 phase is not considered. A compressive stress in the y direction permits to increase the proportion of the M2 variant and leads to a displacement into this direction. A magnetic field in the x direction permits to increase the proportion of the M1 variant. Taking into account the hysterical behavior of the material, the y displacement is therefore controlled by the stress for the reverse direction and by the magnetic field for the forward direction. Therefore, in addition

to "classical" SMA behavior, this alloy permits a rearrangement of martensite variants by a magnetic field at a constant temperature (Gauthier et al., 2006b).

(a)   (b)

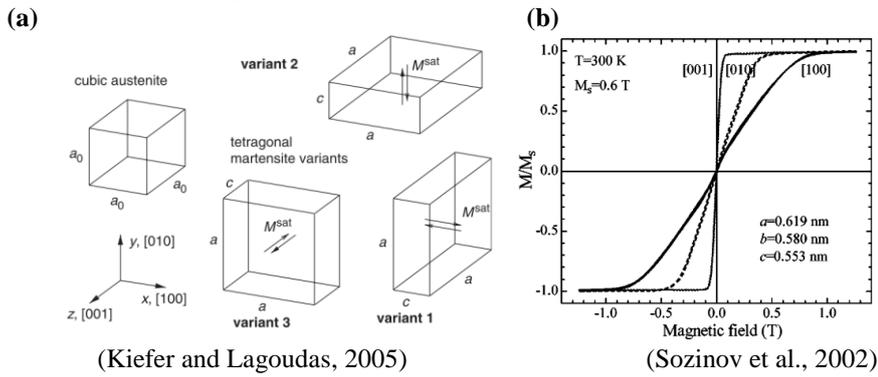(Kiefer and Lagoudas, 2005)   (Sozinov et al., 2002)

Figure 3. (a) Crystal structure of the austenitic phase and the tetragonal martensite variants in NiMnGa. Arrows indicate the possible orientations of the saturation magnetization Msat within each variant; (b) A hysteresis curve for magnetization of a martensite variant in three distinct directions.
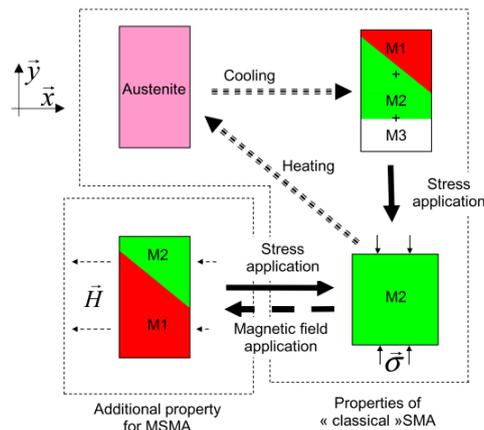

Figure 4. Behavior of a MSMA sample.
(Gauthier et al., 2006b)

3. ACTUATORS WITH MAGNETIC SHAPE MEMORY

Due to the progress on the material research of MSM alloys within the last two decades, the interest for the use of actuators based on MSM alloys as an alternative to conventional actuators increases. The large magnetic field induced strain compared to other solid-state transducers, high-dynamic properties, durability and variability in operation mode make MSM-based actuators especially attractive for applications that are currently restricted by a lower performance of conventional actuators (Effner et al., 2020).

A commonly used MSM actuator design is of linear type: spring/MSMA, the push–push, and the push–pull concept. Holz et al., (2012) and Minorowicz et al., (2022) presents the main operating modes of MSM actuators. Each operating mode refers to a basic possibility to excite the MSM element in the actuator. A combination of more operating modes, in order to fulfill specific constructional or application requirements, can also be taken into consideration. Linear actuators exploit the extension and contraction of the MSM element to generate linear cyclic motion of an end-effector (which is usually directly connected to a MSMA). This concept is popular due to its simplicity, and MSM linear actuators have found applications in pneumatic and hydraulic valves, and even as circuit breakers (Kulagin et al., 2022).

The general principle of the so called spring/MSMA actuator is as follows (Figure 5). The actuating MSM crystal is placed under a moveable piston rod that is connected with a coil spring working as returning mechanism. When a magnetic field is applied to the MSM crystal, the crystal elongates and pushes the piston upwards. At the same time the spring is compressed and exerts force to the MSM element in the opposite direction. This causes a compression of the crystal as soon the magnetic field decreases and as a result, the piston rod moves downwards. Thus, linear movement of the piston rod is performed by varying the strength of the magnetic field. The advantage of this actuation principle is that it is of low complexity and therefore easy to realize. The drawback of this principle is that the MSM element has to overcome the pre-stress force of the spring every time the crystal elongates, which means a loss of the exploitable actuating force. Furthermore, the achievable effective displacement is strongly dependent on the adjustment of the spring (Schlüter et al., 2012).
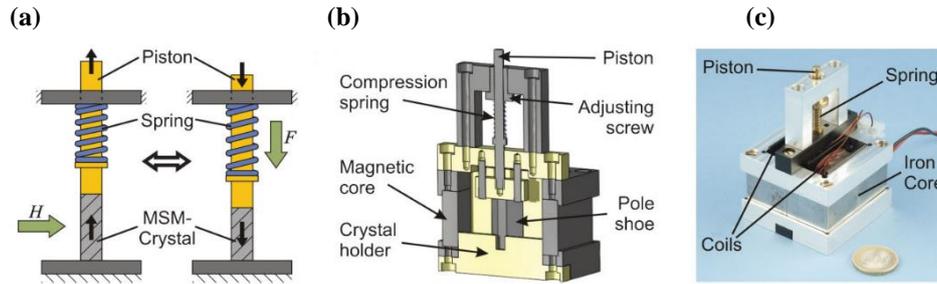
Figure 5. Behavior of a MSMA sample.
(Schlüter et al., 2012)

In the paper of Effner et al., (2020), an actuator with magnetic shape memory in pneumatic valves is presented, that is, the operating principle consists of stretching induced by magnetism and a mechanical readjustment by a spring, therefore classified as spring/MSMA type. According to the authors this conception is the working principle that is most promising to meet the requirements on pneumatic valves, namely a magnetic-induced elongation and a mechanical resetting by a spring. The MSM elements used for this study are specimens cut from the NiMnGa-alloy, provided by ETO Magnetics. With typical sizes of 2 x 3 x 15 mm^3, external flux densities below 1 T, strains of 6% at compressive stresses up to 2 MPa, strokes of almost 1 mm and forces of 10 N to 20 N at frequencies more than 1 kHz can be attained by an MSM element, suiting the desired strokes, forces and dynamic properties of pneumatic valves. Illustration of the initial actuator design is shown in Figure 6.
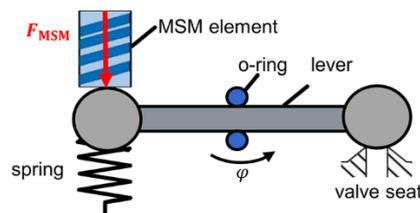

Figure 6. The valve concept consisting of an o-ring beared lever. The MSM element in the air gab of the electromagnet will actuate the valve at one side of the lever and will be reset by a spring.
(Effner et al., 2020)

The authors conclude which challenges can already be overcome and which additional steps are needed to facilitate the progress of the project and allow the maximum benefit of the special characteristics of the MSM alloy. An improvement of the MSM model to respect aspects such as temperature dependence, lifetime and average hysteresis variation according to the sample would allow a more accurate sizing of the valve. A functional prototype of the valve was designed and manufactured as depicted in Figure 7.
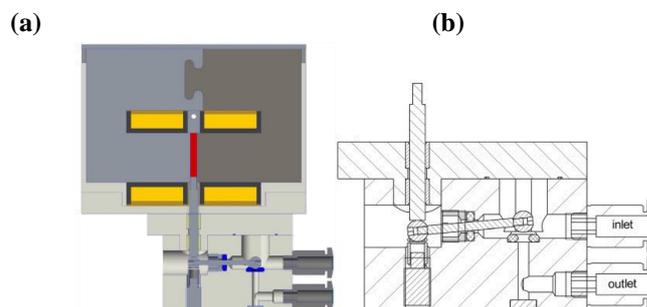

Figure 7. Sectional view of the functional prototype of the valve of the (a) CAD and (b) a drawing of the fluid stage
(Effner et al., 2020)

Spring/MSMA type actuators are the most common in the scientific community and usual applications of the material are actuators that produce linear motion. Tellinen et al., (2002) discuss several magnetic shape memory actuator and their properties and advantages. Flaga and Sapinski, (2011) presents the results of a prototype spring/MSM actuator in which the active element is a rod made of Ni-Mn-Ga alloy and with dimensions of 2 x 1 x 20 mm. In order to exploit this behavior for positioning applications, Yin et al., (2016) presents the design, fabrication and characterization of a linear actuator with return spring based on the magnetic shape memory (MSM) effect with intrinsic position sensing using the displacement dependent change of electrical resistance, Shi et al., (2020) analyzes the principle of magnetically induced

strain and the corresponding constitutive equations, and investigates the magneto-mechanical characteristics of the MSMA sample through measurement carried out on a specially designed experimental setup. Taking advantage of good drive performance, MSMA electromagnetic actuator with spring recovery was designed in detail. Shi et al., (2021) presents a design and performance analysis of hydraulic switching valve driven by magnetic shape memory alloy using the Spring/MSMA type actuators.

Another actuating principle using MSM elements is the so called push–push principle, contrary to the principle of the spring/MSM actuator, where a spring mechanism is used to revoke the induced strain of the MSM crystal, a second crystal is arranged antagonistically to the other MSM element (see Figure 8). These two crystals are connected via a moveable link rod providing the output, i.e., the displacement of the push–push actuator. Without a magnetic field, the displacement remains constant as it is self-supporting. When crystal A is exposed to a magnetic field and crystal B is not, crystal A elongates (case 1). Hence, the link rod is pushed to the right and crystal B is compressed due to the active force of element A. In the opposite case, when crystal B is exposed to a magnetic field and crystal A is not, crystal B elongates (case 2). As a result, the link rod moves to the left and crystal A is compressed. Thus, driving the two magnetic circuits with a controlled current a linear movement of the link rod can be realized (Schlüter et al., 2012).

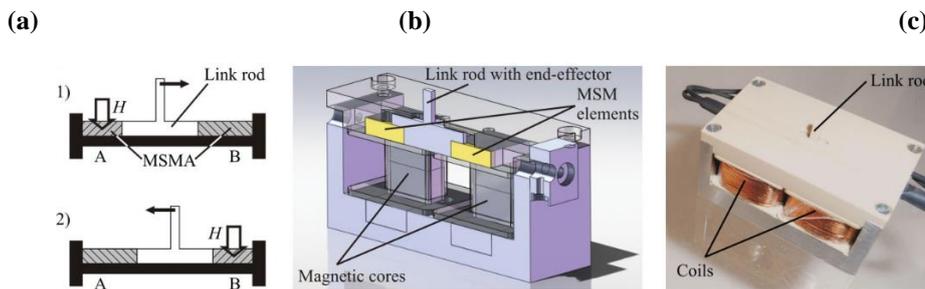**(a)**   **(b)**   **(c)**

Figure 8. (a) Principle, (b) design, and (c) realization of a push–push actuator.
(Schlüter et al., 2012)

Riccardi et al., (2012) characterizes a MSM push-push actuator, and then proposes an identification and control design procedure based on standard PI/PID controllers. Riccardi et al., (2013) discusses in details a control design approach for hysteretic systems with dynamics. The authors propose a method which allows the exploitation of the particular hysteresis characteristic of actuators based on magnetic shape memory alloys, the type push-push actuators. The exploitation of the hysteresis leads to the reduction of the energy losses for some positioning tasks, and can lead to a more compact design of the actuator and of its driving electronics. Moreover, heating phenomena (which are very influent for magnetic shape memory alloys) are reduced. The validity of the proposed method is verified by several experimental results performed on a prototype of push-push actuator.

A motionless drive system, similar to the principle of the push-push type actuator, was built and characterized for localized MSM actuation of Ni–Mn–Ga to be used in creating a drive system for a motionless MSM micropump by Armstrong et al., (2017). A Solid-State Drive System (SSDS) comprising a ferromagnetic yoke, a series of conductive coils, and a current-control circuit was constructed and coupled to an MSM element. The operating principle is shown in Figure 9. By orienting magnetic field sources (the coils) such that they produce flux in opposing directions, their field lines compress at the pole pieces and the flux can be con- trolled and amplified, as shown in Figure 10. A $Ni_{51}Mn_{24.4}Ga_{24.6}$ single crystal was grown with a modified Bridgman furnace. A 27.0 mm by 2.9 mm by 1.0 mm MSM element was cut from this crystal and subjected to a uniform 0.8 T magnetic field parallel to the long axis of the element, placing it in a compressed state with the easy axis of magnetization parallel to the long dimension.

The authors conclude the localized magnetic fields comparable to those of Nd–Fe–B permanent magnets and can be used for the actuation of an MSM element, and as such has the potential to replace the existing driving mechanism of the MSM micropump. At present, large currents are required, but design improvements and magnetic circuit optimization will enable the use of smaller currents. Further development is necessary to translate the discrete creation and destruction of twin variant regions demonstrated in this work to the continuous fluid transfer mechanism of the micropump.
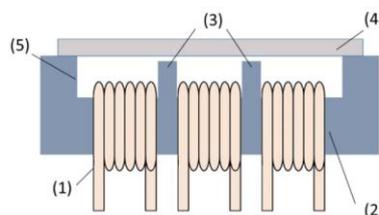

Figure 9. Components of the drive design consisting of a number of electrical coils (1) wrapped around a ferromagnetic core (2) with ferromagnetic pole pieces (3) separating the coils. An MSM element (4) is positioned above the pole pieces and rests upon the ferromagnetic yoke (5), which completes the magnetic circuit.
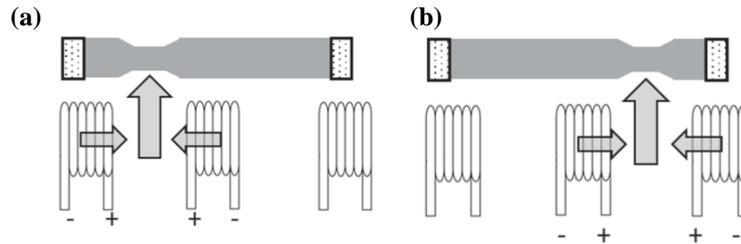(Armstrong et al., 2017)

Figure 10. Graphic representation of the MSM element response to the magnetic fields of the SSDS. (a) Direct current pulses simultaneously in opposition through the left and center electro- magnets, causing a shrinkage above the left pole piece. (b) The center coil's polarity is reversed, the left coil turns off, and the right coil is energized. A shrinkage is now formed above the right pole piece.
(Armstrong et al., 2017)

In the push–pull concept the active material elongates magnetically due to permanent magnets which generate the field inside the MSM element (see Figure 11). Contraction occurs by driving current through the coil, which surrounds the MSM element and the permanent magnets. The resulting magnetic field is vectorially added to the perpendicular field to obtain the contractive field inside the active material. Increasing the current through the cylindrical coil thereby increases causing the element to contract more and more. An external load connected to the actuator push rod would experience active pulling. Upon disconnecting the control current, the MSM actuator jumps back to the state of maximum elongation due to. In contrast to the actuator concepts for MSMA presented in the previous sections, whereby the MSM crystals only can elongate actively and are compressed mechanically, the concept of a push–pull actuator uses magnetically activated contraction as well as magnetically activated elongation. Active pulling as well as active pushing forces are realized by using only one MSM element (Schlüter et al., 2012).
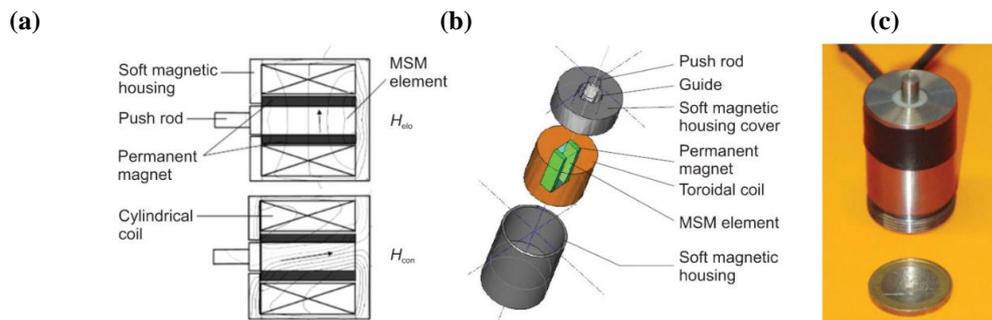

Figure 11. Principle of operation, (a) schematic diagram, (b) exploded assembly drawing, (c) realized prototype of the push–pull actuator.
(Schlüter et al., 2012)

A mulitstable valve technology with magnetic shape memory alloy as passive element activated by a bidirectional solenoid actuator of the push-pull type is presented by Happel et al., (2020), (see Figure 12). In this paper, a passive application for a superelastic Ni-Mn-Ga-alloy is presented by using the MSM element as an accurately defined inner friction in a system of a multistable actuator, in particular a multistable proportional valve. The multistable valve is characterized by a currentless holding of the valve displacement in any position of the stroke. This circumstance makes the concept a very low energy consumption valve, compared to conventional proportional valves with solenoid actuators.
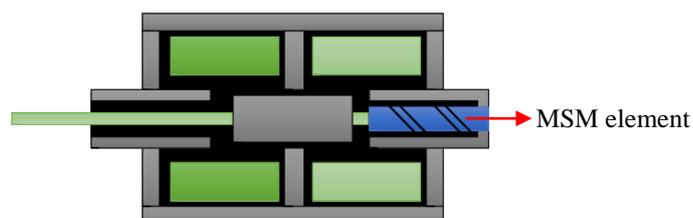

Figure 12. Schematic design of multistable valves with magnetic shape memory alloy as passive element.
(Happel et al., 2020)

In order to solve the problem dealing with the shape recovering by using spring and large excitation power of magnetically controlled shape memory alloy actuator, a new rotating MSM actuator in the differential control way of the two MSMA elements is proposed by Lu et al., (2009). Based on the structures of linear MSMA actuators as one kind of

rotating MSMA actuators is proposed (Figure 13). The operating principle of the MSM actuator consists of the linear displacement produced by the MSMA element under a controllable magnetic field is converted into a rotating motion through the link rod and overrunning clutch which can only turn one-way, two permanent magnets are used to provide the bias magnetic field in order to reduce the control power. The excitation windings are used to produce the controllable magnetic field. Two air gaps are used to force the magnetic flux passing through the MSMA elements. The link rod is used for displacement output of the MSMA rotating actuator.
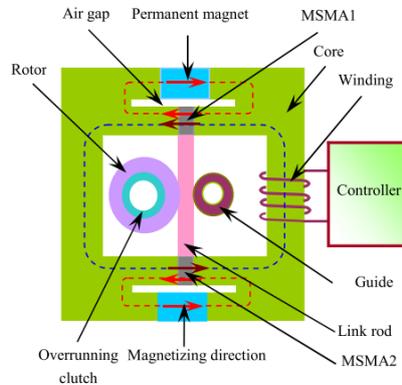

Figure 13. Structure of Differential rotating MSMA actuators.
(Lu et al., 2009)

The authors report that there are still some problems needed to be solved, such as the accurate modeling of the rotating MSMA actuator taking into account the influences of temperature variation, variable permeability, transmission mechanism and so forth.

As presented in this section, all MSM actuator designs are based on design elements used as sources of excitation and restoring forces. Linear actuators with electromagnetic excitation and a spring are the most common design option, 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. 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 a system with no spring, both parts of the cycle require current leading to extra losses and extra power consumption (push-push and push-pull type). However, the size of such an actuator tends to be much larger due to the need for two MSM sticks and two excitation coils. In this type of actuator 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 (Gabdullin et al., 2015).

4. PHENOMENOLOGICAL MODEL FOR MAGNETIC SHAPE MEMORY ACTUATORS

Beyond the material research, which deals with the basic thermo-magneto-mechanical properties of the crystals, the design as well as the control of the actuators displacement is an essential challenge. The MSMA is characterized by saturated hysteresis, which should be compensated in order to obtain good positioning accuracy. Several research efforts are focused on the description of the MFIS of Ni-Mn-Ga and other MSMA materials.

The developed approaches can be divided into physics based models and phenomenological models. The first one uses hysteretic behavior and principles of physics effects. The example is the model, developed for hysteresis of ferromagnetic materials (Minorowicz et al., 2022). Phenomenological models based on thermodynamical principles constitute another alternative to describe MSMA behavior, nowadays are most commonly used and applied. So far, various studies have been conducted to determine the behaviors of MSMA as presented in some research studies below.

Murray et al., (2001) presents a thermodynamic model for field-induced twin-boundary motion describes the main features of the field dependence and stress dependence of the strain. Gauthier et al., (2008) proposes an application of the Lagrangian formalism and its Hamiltonian extension to design, model and control a mechatronic system using magnetic shape memory alloys. Energy-based techniques are used to obtain a coherent modelling of the magnetical, mechanical and thermodynamic phenomena. In this regard, it is important to highlight the phenomenological model proposed Kiefer et al., (2005), (2007), (2008), (2009) that describes magnetic-induced martensitic variant reorientation process under constant mechanical load in MSMA. This model captures the general MSMA behavior presenting good correlation with experimental data.

Qu et al., (2011) presents the model between the output strain and the magnetic field, pre-stress, temperature is presented for MSMA actuator. The characteristics of the output strain are analyzed under the magnetic field, pre-stress and temperature. The experimental results verify the feasibility and effectiveness of the MSMA modeling method for the

output strain. Souza et al., (2018) presents a numerical procedure is proposed to deal with the model nonlinearities. Model predictions are presented for different thermo-magneto-mechanical loadings treating reorientation and phase transformations. Numerical simulations are carried out showing the model capabilities and comparisons with experimental data available in the literature attesting its ability to capture the general thermo-magneto-mechanical behavior of magnetic shape memory alloys. Emu, (2023) introduced a new feature to the existing macro-scale magneto-mechanical model for Ni-Mn-Ga single crystal. Model predictions are compared to experimental data collected on a Ni-Mn-Ga single crystal. Although the model predicts experimental results decently, it does not capture all the features of the experimental data.

5. CONCLUSION

This article presents the types of magnetic shape memory actuators recently reported in the scientific community. Briefly, the main structural properties of Ni-Mn-Ga ternary alloys that influence the application of actuator designs are presented. The projects presented correspond to the most discussed research in the specific literature.

Therefore, we can conclude that the developed prototypes presented demonstrate different concepts using MSM alloys for actuators. All MSM actuator designs are based on design elements used as sources of excitation and restoring forces. As shown, most actuators present a linear application, making this actuator the type are the most studied. It is important to highlight that the material properties influence the project's development, and there are some difficulties that need to be improved, such as the limited temperature range of operation of the Ni-Mn-Ga alloy and its nonlinear behavior due to hysteresis.

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