

## BASIC PROPERTIES OF MAGNETIC SHAPE MEMORY ACTUATORS

J. Tellinen, I. Suorsa, A. Jääskeläinen, I. Aaltio and K. Ullakko  
AdaptaMat Ltd., Helsinki, Finland

### Abstract:

Magnetically controlled shape memory materials are a new way to produce motion and force. The material changes shape in a magnetic field. Shape changes are even 10 percent and response time is less than a millisecond. Usual applications of the material are actuators that produce linear motion. In this article several magnetic shape memory actuators are presented and their properties and advantages are discussed.

### Introduction

Magnetically controlled shape memory (MSM) material is a new way to produce motion and force. The MSM mechanism was suggested in Ref. [1] and demonstrated for a Ni-Mn-Ga alloy in Ref. [2]. The quantitative model of the MSM mechanism and experimental results of large magnetic-field-induced strains of Ni-Mn-Ga were presented in several articles, e.g., in [3-5]. MSM material consists of internal areas, twin variants (see Fig. 1). These variants have different magnetic and crystallographic orientations. When the actuating element made of MSM material is subjected to a magnetic field the proportions of the variants change resulting in the shape change of the element.

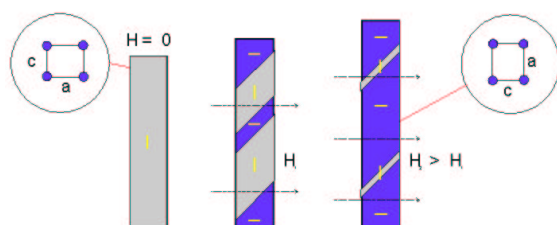


Fig. 1: A simplified presentation of the MSM effect in a single crystalline actuating element.

Figure 1 shows a schematic presentation of the MSM effect in Ni-Mn-Ga. Applying the magnetic field  $H$  to the single variant material causes the other twin variants to appear and grow. When magnetic field strength increases the boundaries between twins move, as amount of preferentially oriented twin variants grow at the expense of the other twin variants. Unit cells of the martensite phase in which MSM effect occurs in Ni-Mn-Ga alloys are tetragonal. The inset on the left in Fig. 1 presents a unit cell of one twin variant. The  $c$  axis, i.e., the shorter lattice axis of the twin variant is aligned along the long axis of the actuating element. In the

other twin variant, the  $c$  axis is perpendicular to the previous variant's  $c$  axis (right inset).  $C$  axis is the easy direction of magnetization of the material. MSM effect is possible if magnetocrystalline anisotropy energy of the material is high enough so as to "turn" the  $c$ -orientation of the unit cell along the magnetic field direction. As a result of the interaction between the magnetic field and twins, the length of the sample increases by the amount of the ratio  $a/c$ . Measured magnetic-induced-strains of the MSM material already reach 10 % (see Fig. 2). This is significantly more than in any other fast responding actuator material. MSM materials research and development is going on in many research laboratories around the world. AdaptaMat is the first company that develops and manufactures MSM materials and actuators.

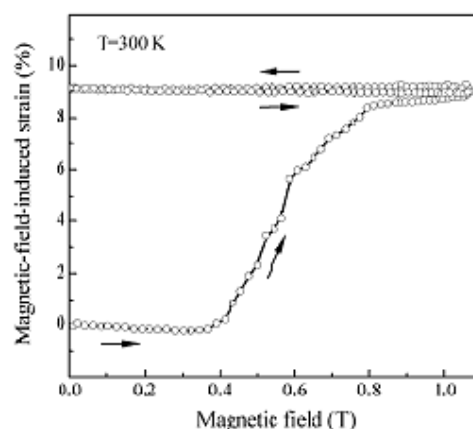


Fig. 2: Magnetic-field-induced strain vs. magnetic field, demonstrating almost 10 % MSM strain achieved with the latest Ni-Mn-Ga developed by AdaptaMat Ltd. [6].

The reversible magnetic-field-induced strain of MSM material is important in applications. Therefore, the material is often pre-stressed by springs. The corresponding strain curves are presented in Fig. 3.

MSM material can be made to change its shape in different ways, such as to elongate axially, bend or twist. So far, actuators developing linear axial motion are most common. In the present article this type of MSM actuators and their properties are discussed. We have concentrated in the motion and the response time. In addition, a measured hysteretic dependence of the motion as a function of the magnetic field and the effect of the external loads are shown. These dynamic and static properties are presented for the example actuators. Based on the results, we discuss on advanced properties of the actuators using MSM material.

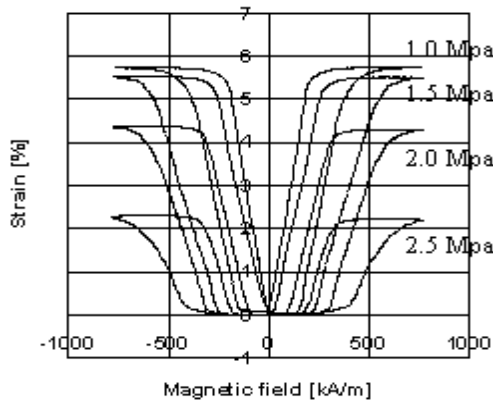


Fig. 3: Magnetic-field-induced strains vs. magnetic field of a Ni-Mn-Ga MSM material.

### Structure of an MSM actuator

MSM actuators need coils that generate the magnetic field subjected to the MSM element. The structure of a basic actuator is presented in Fig. 4. A ferromagnetic core is used to increase and concentrate the field (see Fig 5).

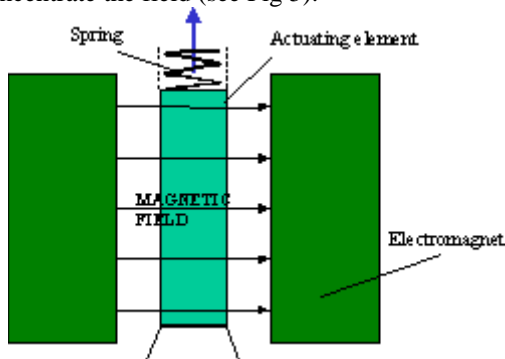


Fig. 4: A basic structure of an MSM actuator.

Properties of the MSM actuator are strongly affected by the core type of the magnetic circuit. Particularly the eddy currents have to be reduced in high frequency applications. In the following part we show two example actuators with different types of magnetic cores. The core type affects especially the maximum operating frequency.

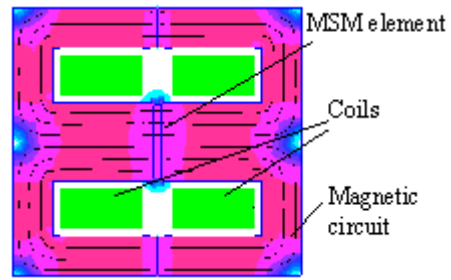


Fig. 5: Cross-section of an MSM actuator and its magnetic flux lines. The MSM element is in the air gap between two coils.

The actuator produces mechanical work. Due to its material properties the MSM element has to be returned by a mechanical force after each cycle. This is usually done with a spring. The MSM element, the moving mass and the spring are the basic components of the mechanical circuit of the MSM actuator. Because the actuator can work at a high frequency, the resonance frequency of the mechanical system is often reached.

If the actuator is used only at a specific frequency and mass, the mechanical resonance frequency can also be used to increase the motion of the system.

### Properties of the MSM actuator

AdaptaMat Ltd produces commercial magnetic shape memory materials. AdaptaMat Ltd has also developed many different types of actuators, where the MSM-material is used as an active element. AdaptaMat has also patented its technology. In the following text we show some properties of these actuators.

#### Actuator 1: A06-3

Actuator A06-3 core is made from high frequency material to reduce eddy currents in the core and to make fast flux changes in the MSM material possible. The actuator is shown in Fig. 6.



Fig. 6: AdaptaMat A06-3 MSM actuator.

The actuator has the MSM element with active length of 15 mm and the frequency response is given in Fig. 7. It is seen that maximum stroke is achieved at frequency 200 Hz. This demonstrates the

mechanical resonance of the system. The blocking force of the actuator is 2.5 N.

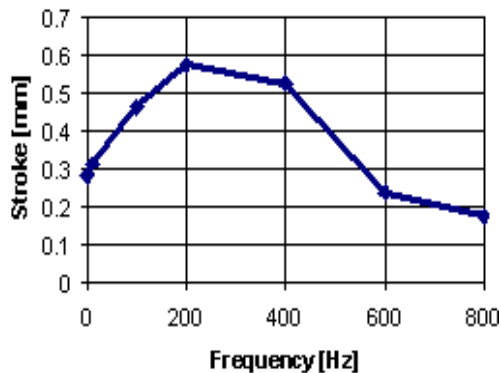


Fig. 7: Measured frequency response of the A06-3 actuator. In each test point the peak-current was 1.5A.

In Fig. 8, the measured current and position curve of similar actuator as A06-3 are shown as a function of time. Due to the high frequency, the sampling of the position measurement can be seen in Fig. 8

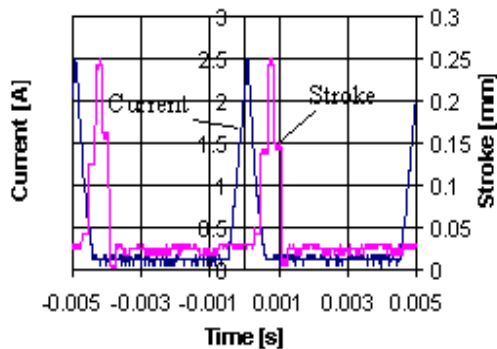


Fig. 8: Measured current and position curves of similar actuator as A06-3.

The measurement shows that the rise time of this actuator is less than 1 ms. The shortest rise times to reach strokes of 3 percent of the actuating element in AdaptaMat's actuators are 0.2 ms. The operating speed of the MSM actuators is limited by the eddy-currents in the core and the inertia of the moving parts of the actuator.

#### Actuator 2: A-1 2000

The actuator A-1 2000 demonstrates the possibility to generate high forces and relatively large motion with MSM material. The actuator is shown in Fig. 9. The core material of the actuator is solid iron, so the actuator is suitable for DC or low frequency operation.

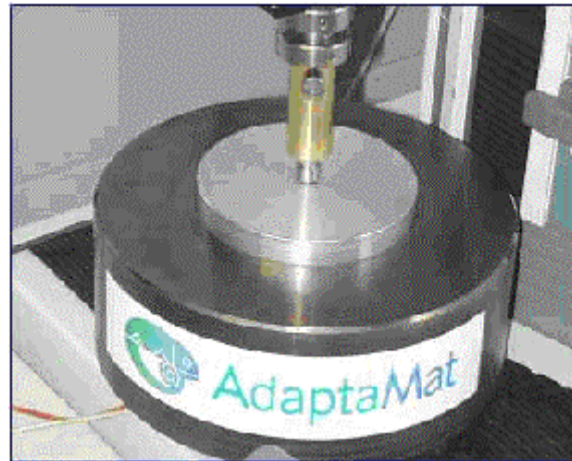


Fig. 9: Actuator A-1 2000 in a tensile test machine. The diameter of the actuator is 260 mm and the height 90 mm.

In Fig. 10 magnetic-field-induced strains of the actuator at a low frequency are shown.

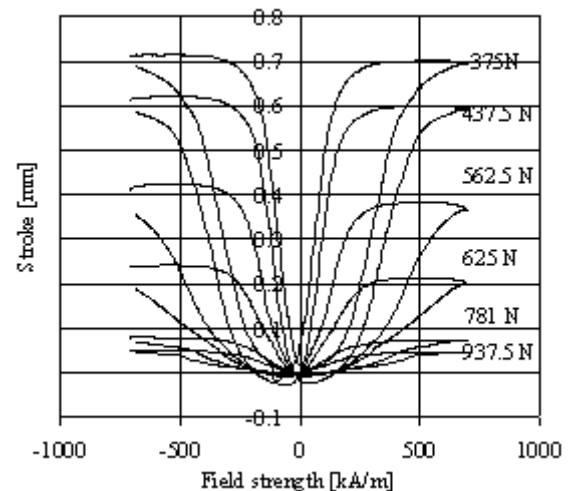


Fig. 10: Field-induced strain when actuator was under the constant compressive load 375-937.5 N.

During these tests the actuator was not equipped fully with MSM elements and the measured values are lower than nominal. However, Fig. 10 shows the operating characteristics and the hysteretic behavior of the actuator. Also it shows the dependence of the stroke on the applied force.

We can combine the results from curves in Fig. 10 and test results at lower stresses to plot the field-induced strain vs. the applied force (see Fig. 11). The maximum field-induced strain is approximately 2.8 % of the length of the MSM element and it is obtained at the stress of 1.25 MPa. This corresponds to values measured earlier from MSM materials.

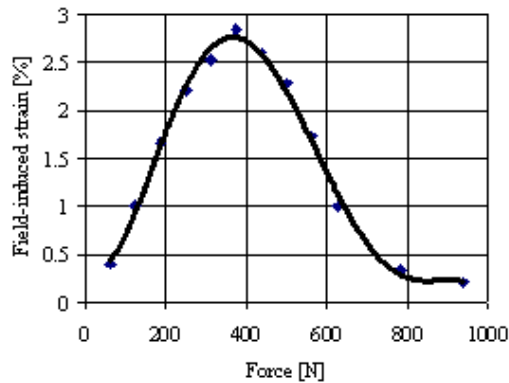


Fig. 11: Maximum field-induced strain vs. load.

### Fatigue of the MSM material in an alternating magnetic field

In high frequency operation of the MSM actuator fatigue properties of the MSM element in an alternating magnetic field are important to know. Fig. 12 shows results of the fatigue test run using the MSM actuator. Stroke of the actuator is about 2 % of the length (10 mm) of the actuating element. The element was loaded with a constant compressive stress of 1 MPa during the fatigue test.

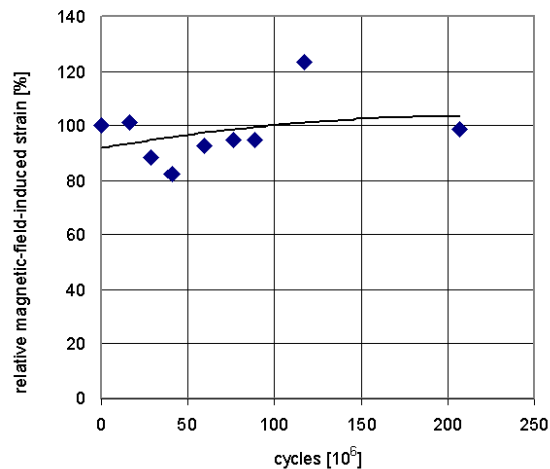


Fig.12: Magnetic-field-induced strain of an MSM actuator as a function of the number of cycles of an alternating magnetic field.

Figure 12 reveals that the stroke of the actuator remains approximately constant without substantial changes during and after  $200 \cdot 10^6$  cycles.

### Conclusions

Properties of linear MSM actuators and Ni-Mn-Ga actuating elements were shown. Based on the results the following conclusions are drawn:

Generated motion of the MSM actuators is fast. Rise time is less than 0.2 ms. Flux generation and the inertia of the moving mass rather than MSM

mechanism of the material limit the rise time. This makes it possible for an actuator to operate at high frequencies and large strokes.

Electromechanical hysteresis properties of the actuator were also studied. Hysteresis exists between the strain and the actuators input current as well as between the strain and stress. Hysteresis is caused by the internal properties of the MSM material. Hysteresis produces losses in the material and complicates the control of some positioning system applications. On the other hand, hysteresis increases vibration damping capacity of the MSM material and avoids vibrations and overshooting of the MSM element in rapid shape changes of the element.

We showed that with MSM actuator large forces can be generated. Up to 1 kN forces were measured, but generally the force depends on the actuator construction and can be much higher. It was also shown that the strain of the MSM actuator depends on the load it has to work against. Optimal load to reach maximal magnetic-field-induced strain is about 1 - 1.5 MPa.

Fatigue test results that showed that stroke of the actuator does not decrease after 200 million cycles of the alternating magnetic field reveal that MSM actuators can operate long times at high frequencies without significant fatigue of the actuating element.

### References

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