Failure mechanisms and high-cycle fatigue of MSM actuators

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Abstract—Magnetic Shape Memory (MSM) materials and actuators may offer an increased fatigue resistance under cycling operation. Proper understanding of relevant fatigue mechanisms will help designing MSM actuators offering clear advantages over today's solutions. The factors influencing fatigue of MSM actuators have not been investigated in detail, which is of prime importance in real applications. Using specially designed prototype actuators these factors are revealed in the present work. Maxwell forces, friction, and resonance effects all contribute to the fatigue resistance of MSM actuators.

1 Introduction

Fatigue of engineering components is a major concern when considering their industrial applications. In MSM materials the fatigue behaviour received recently considerable interest [1,2]. On the other side MSM actuators have several advantages in relation to conventional actuator types. Lifetime could be one of these. The fatigue properties of MSM actuators, however, have not been studied in a more detailed approach, taking into account both the MSM material and the actuator construction. In some first attempts an actuator fatigue life of 200 million [3] and of 425 million cycles [4] has been reported. In perhaps the most comprehensive investigation so far Aaltio et al. studied the fatigue behaviour of MSM materials using a set-up which mechanically elongates and contracts the material [5]. They measured a fatigue life of more than 10^9 cycles, however without taking into account magnetic effects. Furthermore, the strain amplitude was restricted to ± 1%. The situation where the MSM material is set within the air gap of an actuator, giving a strain output of > 4 %, is considerably different, and several additional factors affect the fatigue behaviour and performance. The aim of the present work is to study which parameters have an influence to damage of the MSM element so that finally the lifetime of an actuator could be increased.

2 Experimental actuators

Two types of actuators were designed to study fatigue properties of MSM actuators and investigate failure mechanisms. In the actuator shown in Figure 1 on the left, the pre-stress and the air gap between the MSM element and magnetic circuit parts can be adjusted in order to study geometrical influences on fatigue. In order to visibly observe the motion of the MSM element during actuation with a high speed camera, the magnetic circuit was designed asymmetrically with coils (not visible in Figure 1) placed on one side of the MSM element.

The 2nd type of actuator (Figure 1, right) also allows to externally adjust the pre-stress. Five identical actuators of this type were built and fitted into a test bench so that statistically reliable test results can be obtained.

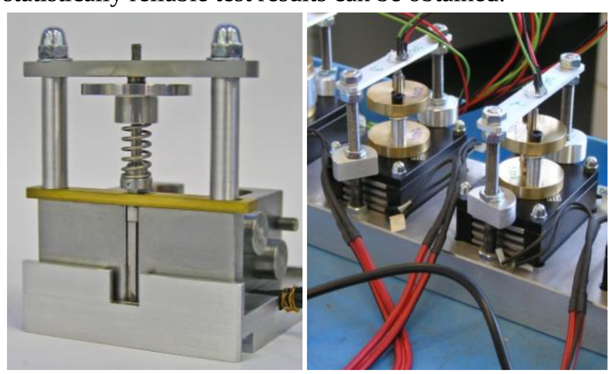

Figure 1. MSM actuators for studying the fatigue behavior.

3 Results

To achieve a magnetically induced reorientation of twin variants in MSM it is necessary to apply a magnetic field that is strong enough to generate a magneto-stress higher than the sum of external and twinning stress. Typically, the external stress results from a spring force F_N which has to be at least as large as the twinning stress to guarantee restoring the initial state. This magnetic field causes a Maxwell force F_M onto the MSM element. If we consider the MSM element as a bending beam the mechanical resistance depends on the geometry of the element itself and we get for the maximum mechanical stress σ_{max} resulting from the forces F_N und F_M

$$\sigma_{max} = \frac{F_N}{wd} + 6\frac{F_M h}{w d^2} \quad (1)$$

where w, d and h are width, depth and height of the MSM element, respectively.

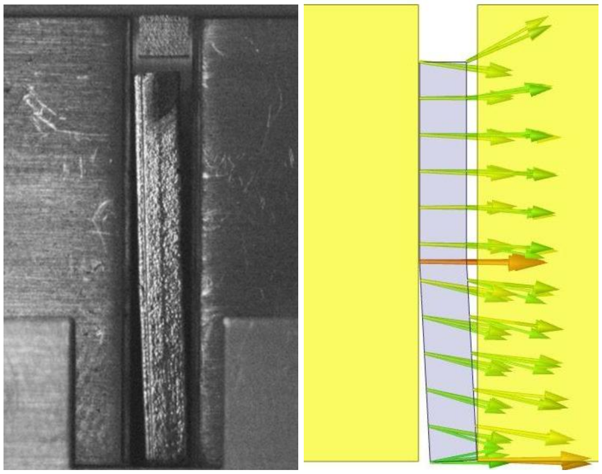

Figure 2. MSM element inside an actuator aligned by Maxwell forces to its magnetically favored position (left) and magneto-static FEM simulation of a MSM actuator (right).

In order to determine the Maxwell forces acting on the MSM, magnetostatic FEM simulations (Figure 2) were performed using FEMM [6] with the MSM aligned in its magnetically favored position as shown in Figure 2 on the left. Additionally, the Maxwell forces were measured using Fuji Prescale Film foils (Figure 3) [6]. These foils were placed in-between the MSM element and the core pieces, and the actuator was energized. The resulting forces cause a colour change of the foils and indicate, locally resolved, the maximum pressure exposure during measurement.

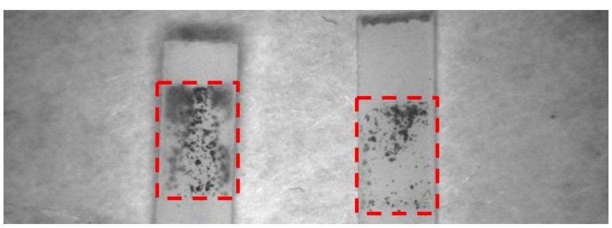

Figure 3. Measurement with Fuji Prescale Film foils show local stress up to about 10 MPa.

The results from experiment and simulation show, that the Maxwell forces may cause a torque of 15 Nmm and finally local stresses of up to about 10 MPa on a 2×3×15 mm³ MSM element. Obviously, the local stress level can dramatically exceed the twinning stress of about 0.5 MPa by more than a magnitude. Therefore, damage and fatigue problems are to be expected.

Furthermore, the Maxwell force contributes to the friction force between the MSM element and the core pieces. This effect was confirmed to be most severe where the relative motion between the MSM element and the adjacent magnetic cores is maximum, which is typically the case at the upper end of the element.

These effects cause degradation of the magneto-mechanical properties relatively fast after less than 1×10^7 cycles (Figure 5). Abrasive wear can cause damages of the twin structure which leads to higher twinning stress and higher magnetic fields for complete elongation.

It was also observed that resonance of the spring-MSM-system can have an impact on fatigue and may destroy the system even faster when it is continuously operated close to its resonance frequency, which is about 200 Hz in our case. However, a detailed discussion of resonance effects has not been the focus of this work.

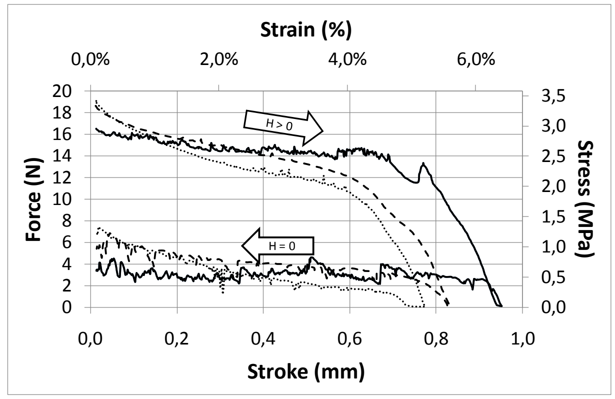

Figure 4. Force-stroke curves of MSM element before testing (continuous), after 8.5×10^6 (dashed), and after 13×10^6 cycles (dotted).

4 Conclusion and Outlook

Results were presented which help to understand failure mechanisms of MSM materials and to improve the high-cycle fatigue behavior of MSM actuators. Based on these results the following conclusions can be drawn.

- Maxwell forces have to be carefully considered when designing high cycle fatigue MSM actuators and can significantly exceed locally the MSM twinning stress.
- Friction and resonance effects shall be taken into account, too, when optimizing MSM actuator fatigue.
- Carefully designed actuator construction which takes into account the MSM material twin structure can significantly improve the actuator fatigue life.

References

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