MODELING OF ADAPTIVE SYSTEMS FOR INTERACTIVE FIBER RUBBER COMPOSITES

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ABSTRACT

Usage of smart materials offers advantages like faster systems, responsive and reliable processes or improved operating characteristics. One solution is the integration of textile actuators based on shape memory alloys (SMA) into fiber-reinforced elastomeric composites. Novel composites from SMAs and elastomeric matrices enable high reversible deflections, controllable deformation and a great variety of movement patterns. For technical usage, a description of the mechanism is required, as well as modelling of the structural components and their properties. The aim of the presented research is a finite element approach as well as description and derivation of manufacturing parameters for relevant material combinations.

Keywords: Shape Memory Alloys, adaptive systems, elastomers, fiber-reinforcement, rubber composites

1. INTRODUCTION

Fiber-reinforced composites are increasingly used in movable components due to their high specific stiffness and strength as well as the ability to tailor mechanical properties according to the respective purposes at very low weight. Current developments tend towards kinematic systems that are being used in logistics and automation engineering as well as automotive and mechanical engineering. Here, especially the low weight of composite structures can be utilized. Through integration of adaptive functionalities in such smart multi-material systems the necessity for additional components is omitted, thus significantly increasing system robustness. Smart materials are a relatively new material class that can actively change their physical and chemical properties through external stimuli. To enable controlled and purposeful structure reaction on external signals, such adaptive smart material based structures contain actuators and sensors as well as signal processing units. Typical fields of usage are robotics, fluid systems and aerospace applications [1]. For this, smart-material-based systems offer a broad variety of possibilities to develop new, innovative products for a multitude of purposes.
The goal of the presented work is to create fast responding adaptive structures at low reaction times that are also exhibiting large deflections and transmitting high forces. Currently, generation of such structures is not possible. The approach to achieve this is combining high-force-generating Shape Memory Alloys (SMAs) with fast reacting Dielectric Elastomer Actuators (DEAs) that are both embedded in a textile reinforcing structures for low-modulus elastomer matrices. The herein presented work focuses on the SMA aspect and the steps necessary for creating a simulation model suited for the description of the deformation behavior of such elastomeric composite structures.

2. STATE OF THE ART

2.1. Smart materials and adaptive structures

The most promising smart materials to be used in this work are those that can change stiffness or geometry under magnetic, thermal or electrical influence. Noteworthy examples of such smart materials are piezoelectric materials like PZT (lead zirconate titanate) ceramics, electroactive polymers (EAP) and shape memory materials based on metallic SMA [1]. The latter are the most relevant option for this work, since they are the only class of smart materials that can generate both large deformations and large forces on activation. SMA in wire-shape are also commercially available in great variety, making them well suited for the planned work.

2.2. Material behavior of Shape Memory Alloys

SMAs are a special material class that regains initially applied deformation through heating above the material specific transformation temperature [1]. This effect is called shape memory effect (SME) and is based on the materials' ability to perform a diffusionless solid-phase-transformation between the martensite phase, which is stable below the transformation temperature and the austenite phase, which is stable above the transformation temperature [1]. The transformation between martensite and austenite can be induced by heating, mechanical loading or a combination of mechanical load and heating. The shape memory effect can be divided into two different types, the one-way-effect (OWSME) and the two-way effect (TWSME). Due to low usable forces and strains [2], the TWSME is not considered here.

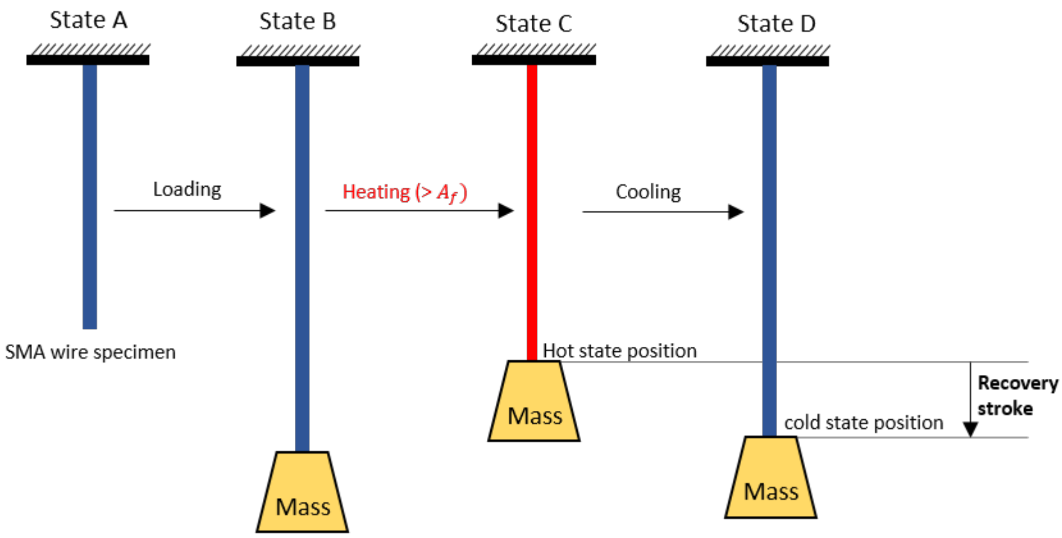

Figure 1: Concept of the Shape Memory Effect, based on [3]

Following the OWSME is described. As can be seen from figure 1, in the initial state A, the wire is first deformed by mechanical load towards state B. By heating the wire during state B above the upper end of the transformation temperature range (Af), the structure transforms from martensite to austenite. This leads to a contraction of the wire back towards the initial state A, which is not completely achieved due to the elastic deformation induced by the constant mechanical load. The amount of the contraction is called stroke and represents the usable wire movement for actuation, which is usually given as a percentage value. Finally, upon cooling the wire transforms back to martensite. Due to the applied mechanical load acting as a resetting force, the wire instantaneously elongates again towards State B. Without the mechanical load, the wire would not recover the stroke and stay in the shortened state C. Thus, with a resetting force it is possible to repeatedly switch back and forth between the States C and D. That effect - combining the OWSME with a reset force - is called the Extrinsic Two-Way-Effect and is the most used concept for the usage of SMAs as actuators. The actuation frequency of this kind of SMA is limited by the speed of the heating and cooling process, the latter being the biggest obstacle for composite structures with integrated SMA actuators. In order to model the SMA material, several significant properties must be obtained, namely the transformation temperature range, the amount of usable recovery stroke as well as the mechanical behavior of both martensite and austenite phase. Therefore, a thermomechanical characterization is necessary.

2.3. Textile technology

Functional textiles will enable novel 2D- and 3D-structures with specifically adjustable properties as well as other additional functions. The mechanical behaviour of textile-reinforced composites can be adjusted in a wide range by usage of textile processes as well as through after treatment of the textiles [4]. Actuators and sensors have been integrated with textile processes like tailored-fiber-placement, realizing simple actuator and sensor functionalities. For this, mostly duroplastic matrix-systems were used [5 – 8], which impede the generation of large deformations due to their high stiffnesses. The development of innovative 2D- and 3D reinforcing stuctures for elastomeric matrix systems will enable complex deformation or movement pattern and is being pursued at a later stage of this research using the simulation tools developed within this paper.

3. METHODS AND EXPERIMENTAL DESIGN
3.1. Methods

For the goal of creating actively deformable structures with SMA wires and predicting their deformation behaviour by means of a simulation model, a concept for a simple bending actuator will be used as a starting point. Furthermore, the mechanical behaviour of SMA wires will be investigated with the goal of estimating the obtainable stroke, mechanical properties of martensite and austenite as well as influences of rubber crosslinking temperatures on the stroke.

3.2. Deformation mechanism

The simplest mechanism useable as large deflection mechanism is a bending beam. The principle is closely related to a Bowden cable. The actuator structure is set up through integrating an SMA wire that is well set-off from the neutral axis, into a beam with rectangular cross-section (cf. Figure 3).

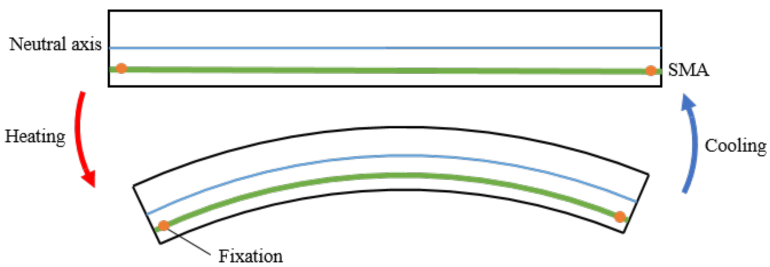

Figure 2. Bending beam principle [7]

For optimal functionality, the SMA wire only needs to be fixed at its two ends, while in between a “channel” enables a free wire movement along its longitudinal axis. Contacting the SMA wire at the fixation points enables thermal activation through Joule heat [9]. Upon activation, the OWSME causes the wire shortening and thus generation of a force onto the structure. Due to the offset from the neutral axis that force creates a momentum, thus a bending of the beam.

Additionally, a distributed load acts over the length of the beam due to the bent beam putting pressure on the surrounding structure [10]. The deflection for large deformation is estimated by the bending angle.

4. THERMOMECHANICAL CHARACTERIZATION OF SMA

The integration of SMA wires into elastomeric matrices takes place via crosslinking of the respective elastomer systems (e.g. nitrile rubber (NBR)) at temperatures around 120-150°C within 30-60 minutes [11]. The challenge is that such a heat treatment would activate the SMA wires and thus potentially damages the structural linkage of the SMA to the elastomer system. In order to understand and describe this effect, experiments were carried out to estimate the effect of restraining the wires during the transformation stroke. The results are shown in Figure 2.

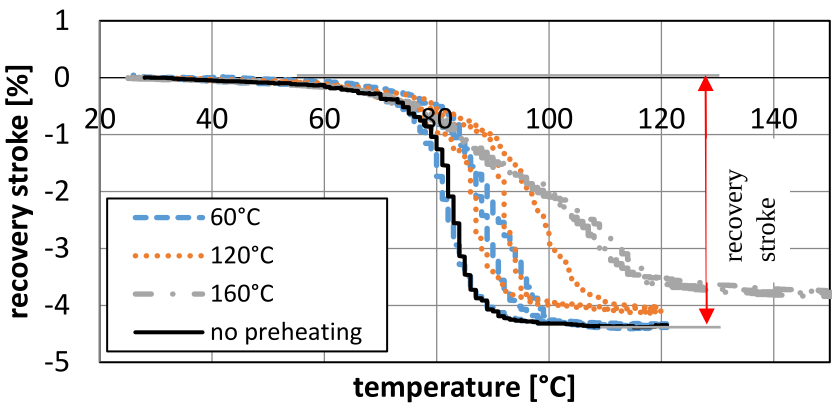

Figure 3: Reduction of SMA wire stroke after preheating with fixation

During the experiment both ends of the wires were fixed to an external component resulting in hindering the wire from contracting during activation. After this preheating, the stroke measurement was carried out. As can be seen from figure 2 the result is a significant loss of the usable stroke at higher temperatures. Therefore, elastomer system with lower crosslinking temperatures will be considered in order to ensure the maximum usable stroke.

5. SIMULATION

For the simulation of SMA material, the commercially available model by Souza et al. [12], implemented into ANSYS® is used, which is capable of modeling the OWSME as well as the extrinsic two way effect. Calibrating the material model requires information from four experiments: tensile test of martensite, tensile test of austenite, stroke activation test and DSC [13]. Calibration of the material model was carried out by setting start values and iterative fitting of the simulation curve to the experimental data.
In order to model the extrinsic two way effect, a new modeling approach for applying prestrain onto the SMA wires was developed: In the first load step, all contact boundary conditions of the wires are initially deactivated, only the fixation at one end stays active. A tensile load is applied to the wires, stretching them to their full stroke length. After allowing for elastic setback, the contact boundary conditions are reactivated, fixating both ends of the wire to the elastomer surface. The wires are now prestrained, so that the shape memory effect can be activated by assigning a temperature directly to the wire elements.

The NBR elastomer material was simulated by usage of a hyperelastic material model. The second order polynomial model was found to be best suited for curve fitting with test data of the elastomer material. To model the interaction of the wires embedded close to the surface of the matrix, the "No Separation" contact formulation was used [14], since the wires are supposed to move freely relative to the surface but stay in a defined distance to the surface. Both the elastomer matrix and the wires were modeled with 3D volume elements. With this, the bending deformation can be simulated as shown in Figure 5.

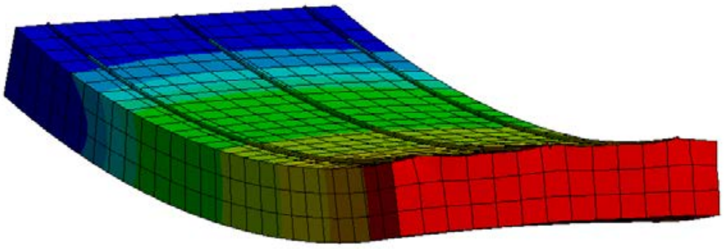

Figure 4: Model of elastomer bending beam with embedded SMA wires during thermal activation

6. CONCLUSION

The ongoing research at ITM aims at the creation of novel adaptive structures based on SMA wires integrated into elastomeric matrices to form rubber composites. For this, a basic understanding of the SMA material behavior and its usable actuation effects was necessary and presented, together with a simple bending mechanism suited for usage with SMA wires. Furthermore, relevant material tests of SMA wires were carried out. It was shown that high temperatures during crosslinking reduces the usable stroke of the SMA actuators. Therefore, low temperature elastomer recipes should be used for manufacturing functional actuator structures. For future work, a textile-based fixation of the SMA wires is planned in order to reduce the amount of necessary working steps. Another future approach to be studied regarding the feasibility is the integration of the SMA wires into the composite structure after crosslinking.

For the goal of developing and dimensioning such adaptive structures, a first simulation model is presented, which is capable of representing the complex material mechanisms and interactions. By calibration of a SMA material model with experimental data, the material behavior can be described. In order to accurately represent the shape memory effect with resetting force, a new modeling approach was developed. Here, the prestrain is applied in an additional load step, after which the fixation onto the elastomer structure is established by stepwise activation of boundary conditions. The shape memory effect is then activated by applying temperature to the wires. It was shown that the chosen modeling approach is well suited for generating an impression of the deformation principle and predict deformations for different configurations of SMA-based actuators with elastomer matrices.

Future modeling approaches should take into account the behavior of layered elastomer composites with fiber reinforcement layers. A more detailed consideration of possible fixation mechanisms like textile-based and material interface bonding will also be necessary. Furthermore, more complex deformation modes than bending will be considered. The model will then be used for dimensioning the arrangement and fixation of the SMA wires within the textile structure. Based on these simulative developments, specific advancements of the adaptive structures will be carried out.

7. ACKNOWLEDGMENTS

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