Industrial Applications of Shape Memory Alloys – Potentials and Limitations

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Abstract

Shape Memory Alloys are well known and established in medical engineering. In recent years their importance considering industrial applications also increased. Especially the high specific work load of the material and the simple working principle of SMA actuator systems possess them to be a suitable alternative to conventional drives. The benefits of the technology directly address the main demands on actuator technologies like miniaturisation, lightweight design and costs. Further SMAs can be an alternative to substitute rare earth metals. In the paper we present the status quo of SMA technology. The shape memory effect as a basis for understanding the working principles of such actuators is described. Beyond that mechanical design rules are explained. That covers the three possible actuating principles constant- and spring loaded and antagonistically arranged SMA actuators. Besides simple switching applications, there are rather complex controlled SMA actuators using external sensors or inherent resistance feedback. Control principles for both approaches are presented. To show potentials but also the limitations of SMA actuators, applications from different markets with different demands are described. They specify the certain challenges which have to be overcome before a comprehensive market acceptance of SMAs in industrial applications can be expected. The estimated developments in the future will be discussed further.

1 Introduction

Due to intense material research in recent years the performance of thermal shape-memory-alloys (SMA) increased considerably, which resulted in numerous new application fields for this kind of intelligent material. The most promising fields of application are determined by the specific actuation characteristics of the material. In addition to thermal activation a very important property is the very high specific workload of actuators made from SMA. A comparison of the volume specific workload of different actuator types is shown in Figure 1 [1]. From the graph it is obvious that SMA-actuators reach very high work load levels which are nearly five orders of magnitude higher than those obtained for small DC-drives. Research at the Fraunhofer IWU is therefore focused on the development of small SMA-drives. The major benefits are a significant reduction in scale, weight, and costs of such drives. Also there is no need of rare earth metals in contrast to solenoid actuators

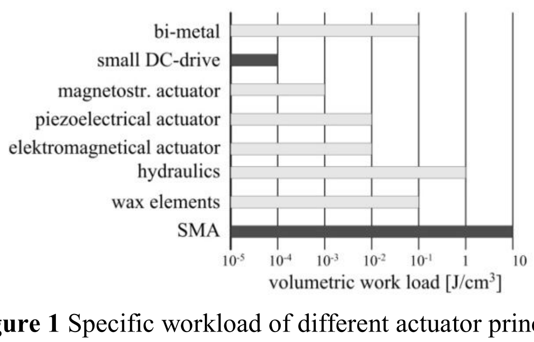

Figure 1 Specific workload of different actuator principles [1]

1.1 Material basics

Thermal shape memory alloys have the special ability to "remember" and re-assume their original shape following permanent plastic distortion below a specific critical temperature by means of heating up above this temperature. A reversible austenite-martensite phase transformation is required for the development of the shape memory effect. Analogous to steel the high temperature phase is called austenite and the low temperature phase is called martensite. In an ideal situation the austenite phase is converted into the martensite phase as a result of shear. Due to diffusion-free rearrangement processes in relation to the atoms this generates a change in the stacking sequence of the crystal lattice levels and therefore a change in the structure of the crystal lattice.

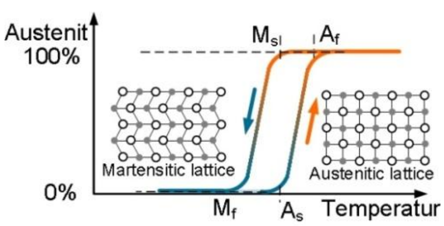

Figure 2 Phase transformation process

Heating the wire causes the described phase transition (see Figure 2). The transformation from martensite into austenite starts at the temperature A_s and is finished at A_f. Above the austenite finish-temperature the lattice structure is fully austenitic. During this process some thermal energy is converted into mechanical energy and can be used for actuation. Cooling down the wire induces the retransformation from austenite to martensite. It starts at M_s and is finished when reaching the martensite finish temperature M_f. As shown in Figure 2 there are hysteresis effects in the temperature regime. The absolute values of the temperatures strongly depend on the alloy composition and the previously done heat treatment process. Values for commonly used alloys are given in Table 1. The most applied material is NiTi, also called Nitinol. NiTi is commercially available as wire, rod, tube or sheet. Actuator bodies can be made out of these semi-finished products by machining processes.

	Transformation temperature Af (°C)	Hysteresis(A_f-M_s) [K]
NiTi	-100…120 °C	15…30 K
NiTiCu	-100…120 °C	10…20 K
CuAlNi	-150…200 °C	20…30 K
CuZnAl	-200…120 °C	10…20 K

Table 1 Transition temperatures of different SMA [2], [3]

Due to the different lattice structures consequently two different stress-strain-curves exist as shown in Figure 3 left. In the low-temperature martensitic phase a small Hook region is followed from a so-called plateau-stress where the wire can be easily deflected almost without increasing the applied external stress. After setting the stress to zero, a plastic distortion remains at the wire. In the high temperature austenitic phase the Hook region is significantly wider, the Young-modulus is two to three times higher and applying a high amount of stress causes a so called super-elastic-behavior.

2 Mechanical Design

During the phase transition from martensite to austenite (heating) the wire is able to perform mechanical work. The amount of work depends on the mechanical boundary conditions of the wire. In case of a free wire the work would be zero, but the actuator deflection would be maximum. In contrast, blocking the wire causes a very high actuation force but no deflection. The work output is also zero. Using a spring with a defined stiffness as boundary element instead causes a deflection as well as a reaction force and therefore a usable workload. The amount of that workload depends on the stress-strain-curves of the used material and the design of the spring. The mechanical design of such actuators has been described previously and details can be found in [4].

Pre-stretched one-way SMA wires contract by heating above a certain austenite start temperature. However, without an applied load these wires do not deform to their origin position upon cooling. Systems using one-way SMA wires therefore have to be used in combination with a force creating (pull back) component as for instance an applied constant load (mass), a spring or an antagonistically arranged second SMA wire.

2.1 Constant load

The first approach to realize a pull-back force is applying a constant load (mass) on it. Figure 3 right shows the mechanical principle. The cold actuator in martensite state is strained by the load until it reaches a certain stress level (see Figure 3 left solid line). Heating the wire causes the described phase transformation and results in a contraction of the wire by ΔL until it reaches the austenite stress-strain-curve. Cooling the wire results in a reverse phase transformation and the load pulls the wire back as far as the complete martensite state is reached. The amount of work that is performed to move the actuator is defined as

$$W_{PB} = m \cdot g \cdot \Delta L = \sigma_{\max M} \cdot \frac{\pi \cdot d^2}{4} \cdot \Delta L \qquad (1)$$

The value of usable actuator work is

$$W_A = (\sigma_{\max A} - \sigma_{\max M}) \frac{\pi \cdot d^2}{4} \cdot \Delta L \qquad (2)$$

Where $\sigma_{\max A/M}$ is the maximum applicable stress in austenite/martensite state (affecting the fatigue behavior) and d represents the diameter of the wire.

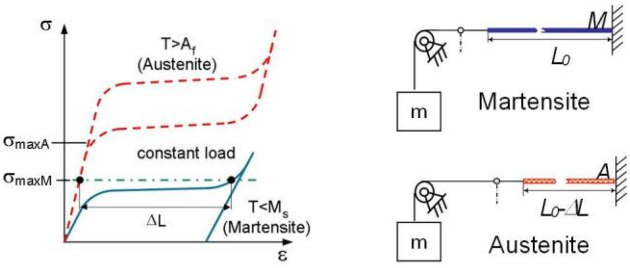

Figure 3 SMA working against constant load

2.2 Spring load

Using a pre tensioned spring with a defined stiffness (Figure 4 right) as pull-back element instead, also causes a deflection as well as a reaction force. However, the applied stress on the wire increases due to the rising force characteristics of the spring.

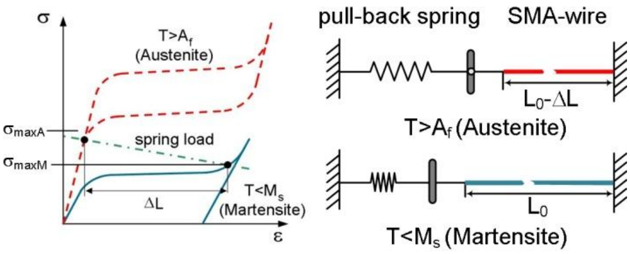

Figure 4: SMA working against spring load

The sum of work that is performed to move the actuator is

$$W_{PB} = \sigma_{\max M} \cdot \frac{\pi \cdot d^2}{4} \cdot \Delta L + \frac{1}{2} c \cdot \Delta L^2 \qquad (3)$$

The amount of usable actuator work is

$$W_A = (\sigma_{\max A} - \sigma_{\max M}) \frac{\pi \cdot d^2}{4} \cdot \Delta L - \frac{1}{2} \cdot c \cdot \Delta L^2 \qquad (4)$$

It is easily visible that the amount of usable work decreases (depending on c) compared to the constantly loaded wire. Furthermore the usable force of the actuator decreases with an increasing deflection of the spring. This behavior is disadvantageous for the application as position controlled drive because in most cases it is necessary to offer a constant amount of usable force over the whole range of the actuator.

2.3 Antagonistic arrangement

Compared to the other actuator principles the antagonistic arrangement has the advantage that only the necessary pre-tension is applied to the SMA wire. Figure 5 shows that the pre-tension on the wire is significantly lower (dash-dot-line of the load wire).

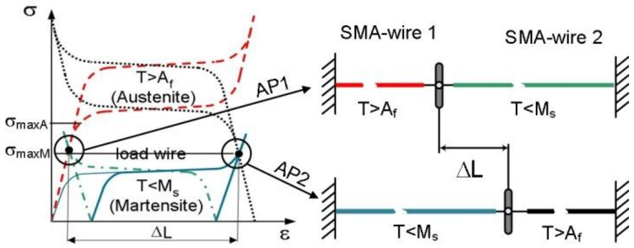

Figure 5 SMA working against antagonistic SMA wire

The amount of work that is performed to move the actuator is defined by

$$W_{PB} = \int_{\varepsilon_0}^{\varepsilon_{\Delta L}} \sigma(\varepsilon)d\varepsilon \tag{5}$$

The amount of usable actuator work is defined by

$$W_A = \sigma_{\max A} \cdot \frac{\pi \cdot d^2}{4} \cdot \Delta L - \int_{\varepsilon_0}^{\varepsilon_{\Delta L}} \sigma(\varepsilon)d\varepsilon \tag{6}$$

As visible in Figure 5 the usable work of the actuator is higher compared to the other actuator principles because only a minimum of energy is needed for moving the actuator. As described in [5] switching off the energy supply is not possible. In that case the actuator would release his tension and though move by the amount of his elastic deformation (dash-dot-line) and cause a non-tolerable positioning error.

Another important aspect the actuator principles have to be investigated for is the dynamics. It has to be remarked, that the discussion in this paper only corresponds with heating the wire. The cooling procedure rather necessitates other aspects to be considered. The dynamic behavior of an SMA actuator is defined by the phase transition temperatures. As described in [6] there is a characteristic transfer time constant that defines the transfer from martensite to austenite. This time constant decreases with an increasing difference between A_s- and A_f-temperature. It can be shown that this difference depends on the actuator principle (constant/ decreasing/increasing load). Hence the actuator principle wire against spring and the antagonistic arrangement should possess a faster transfer behavior compared to the constant load arrangement.

3 Control Design

The material behavior of SMAs is strongly nonlinear, which makes the realization of the position control relatively ambitious. Nevertheless linear control approaches as described in [7] are a suitable choice. This is caused by the simplicity of the algorithms and the possibility to optimize the controller only by adjusting a few parameters. Furthermore such control algorithms are relatively robust concerning possible variations in actuator parameters. Overall linear controllers offer the possibility to realize adequate closed loop controls without profound knowledge in control design.

3.1 External sensing

Controlled drives for positioning applications always require a closed loop control of the actual position. Due to the high precision demands of most applications the control loop necessitates an accurate external position sensor. This can be achieved for example by a laser triangulation sensor. Under certain circumstances as described in [8] the plant of an SMA wire can be described by a simple first order lag element that can be controlled by a simple PI-controller. However, the integral part of the controller is always set as a compromise between heating and cooling and would be different for the three actuator principles. Due to the necessarily comparability of the actuator principles this work only focuses on the application of simple proportional-controllers.

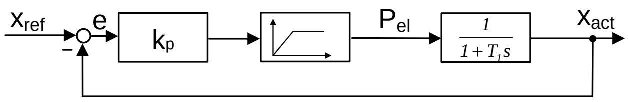

Figure 6 Simplified control loop of an SMA wire

Figure shows the simplified control loop of a single SMA wire that consists of a P-controller, a power limitation and the plant as a first order lag element.

3.2 Internal resistance feedback

The development of applications with continuous positioning demands always requires a closed loop control of the actuator stroke. These control loops usually necessitate an external position sensor. SMA control loops rather can be designed without an external position sensor, because the material behavior possesses to get information about the actual stroke only by measuring the resistance [9]. During the phase transformation from martensite to austenitic lattice and the so involved changes in the structure of the SMA-material, the status of transformation correlates with the electrical resistance. In fact the lattice structure in austenite state is more regular than in martensite state. Therefore the specific electrical resistance of austenite is significantly smaller than the one of martensite. The information of the actual wire stroke can be determined by measuring the electrical resistance during positioning operations. Compared to the implementation of an external position sensor this can be achieved by significantly less effort, because an electrical interface is needed anyway to control the power input of the actuator.

As shown in the references [7], [10] there are different possibilities to model the length-resistance-correlation of SMA-wires. That varies from elementary linear approaches to complex approaches considering the temperature influences on the specific resistance and the changing geometry during the deflection of the wire. According to the intended application an implementation on a rapid prototyping system is necessary. In combination with the requirements regarding the positioning accuracy of the intended positioning devices using a linear approach seem to be adequate. In [4] a linear interpolation of the specific resistance from martensite ρ_A to austenite ρ_M in the form:

$$R = \left[\xi \cdot \rho_M + 1-\xi \;\; \rho_A\right] \cdot \frac{L_0}{A_q} \tag{7}$$

is published. The elimination of the martensite amount ξ results in a linear correlation of wire length and resistance:

$$L = L_M - \frac{\Delta L_{rev}}{\Delta R_{rev}} \cdot \;\; R_M - R \;\; . \tag{8}$$

In this equation ΔL_{rev} and ΔR_{rev} are the maximal differences of the wire resistance and the achievable stroke during the phase transformation (see Figure).

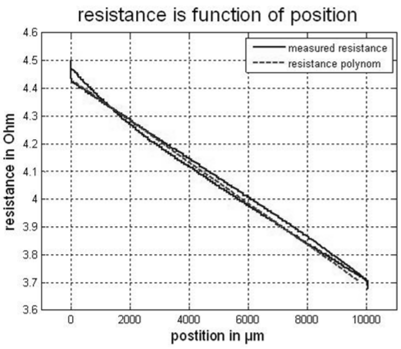

Figure 7 Length-resistance-correlation (X2-wire Memry)

Implementing the correlation to transform a given reference position L_{ref} into a reference resistance R_{ref} as described in the following chapter requires a solution of the reference resistance:

$$R_{ref} = R_M - \frac{\Delta R_{rev}}{\Delta L_{rev}} \cdot L_{ref} \tag{9}$$

It has to be remarked, that the reference position L_{ref} always represents a contraction of the wire and decreases from the maximum wire length in full martensite state. The required resistance and stroke values can be determined by measurements or calculations regarding the geometrical dimensions and the material parameters of the wire. The control structure equals the control loop in Figure with an additional resistance calculation in the feedback loop.

3.3 Control concept for antagonistic wires

The existence of two SMA actuators in antagonistic arrangement necessitates an enlargement of the plant by an additional first order lag element that represents the second SMA wire. The wires are coupled at their mechanical output (see Figure 8). As described in [10] the phase transition temperatures of SMAs increase with an increasing tension. This correlation possesses to raise these temperatures in the first wire by heating the second [5]. Due to the increasing difference between ambient and phase transformation temperatures in the first wire the transformation from austenite to martensite will occur faster. To benefit from this effect the control concept bases on splitting the control value. As shown in Figure the first actuator only acts in case of positive control values and the second actuator only acts for negative values.

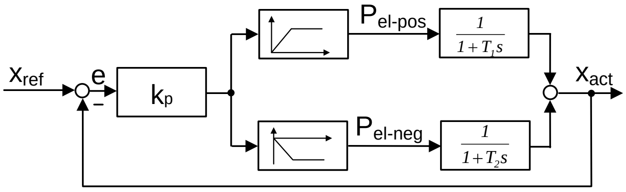

Figure 8 Control concept for the antagonistic arrangement

Due to the coupling between the SMA wires it has to be considered that only one wire is heated at a certain time. This is realized by the limitation of the mechanical tension between the wires. If the tension exceeds a defined constant the control value is set to zero either until the tension decreases or the control values sign changes.

4 Industrial Applications

Generally there are two possible activation concepts for SMA actuators. Firstly the actuator can be activated by means of external heating. For small SMA volumes electrical current can be applied for heating as a consequence of the electrical resistance. Bigger actuators necessitate heating elements to be activated in indirect form. Both approaches possess to realize a fully controllable actuator, but however they require additional power sources and control.

The second activation concept is rather simple considering the system costs but very complex regarding design. The approach is to use the thermal energy of processes combined with the characteristics of the SMA actuator to affect the thermodynamic process parameters. Such systems are able to work completely independent since the SMA enables to combine the functions of sensor, actuator and even mechanical structure. The activation behavior of the actuator is directly linked to the process. Consequently it cannot be triggered externally but nevertheless be used for measuring purposes. The design process of such system is described in [11]. Here an SMA actuator is used for compensating thermally induced deformations of a ball screw drive applied in machine tools.

4.1 Release Actuators

A common actuation task is simply releasing flaps, locks and housing parts. The requirements of such systems can often be fulfilled by SMA actuators. Most of them only have to deliver some Newtons force and a few millimeters of stroke. A continuous position control is normally not required. Nowadays solenoid actuators are the commonly used approach to realize such positioning tasks. Figure 9 (left) shows an actuator for releasing the overhead oxygen masks in an aircraft. If the cabin pressure decreases under a certain level, the actuator releases the coverage and the masks fall down. The system consists of two main parts. The release mechanism including a manual release function consists of several springs and mechanical components for guiding and clamping purposes. The energy conversion from electrical to mechanical energy is realized by a solenoid element which is also the biggest and by far heaviest part of the system. The solenoid creates a stroke of 2 mm and a force of 15N.

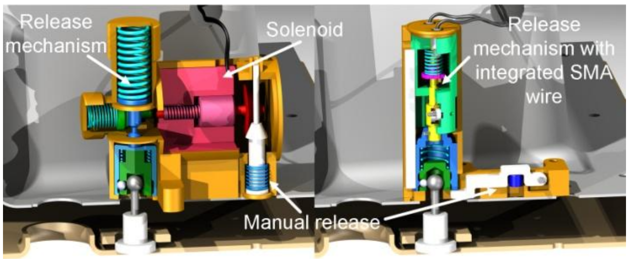

Figure 9 Release actuators: solenoid (left), SMA (right)

The same positioning parameters can be easily relized by an SMA actuator. The spring load principle as described in section 2 is the most feasible designing for the actuator. Like in the solenoid actuator the release functionality is fixed by springs and clamping elements. The energy transformation is rather done by an SMA wire heated by a short current pulse. Due to the phase transformation (as described in Section 1) the wire contracts and the coverage is released. The specific workload of the SMA is much higher than the workload of the solenoid. Therefore a wire of only 0.2 mm in diameter and 25 mm length is necessary to achieve the desired stroke and force. Hence it is possible to integrate the wire into the release mechanism. Thus no extra cross section for the energy transformation mechanism is required. A comparison of the two solutions is shown in Table 2.

	Solenoid actuator	SMA actuator	Improvement [%]
Weight	82 g	28 g	66%
Cross section	21 cm^3	10 cm^3	53%
Power	ca. 11 W	ca. 4,4 W	60%
Number of parts	ca. 30	ca. 20	33%

Table 2 Properties of release actuator shown in Figure 9

4.2 Position controlled actuator

Besides switching drives there is an increasing demand for position controlled actuators. The range of applications is versatile and covers automotive applications like headlight adjustment systems or flaps for air conditioning as well as industrial applications like driving valves or grippers. Due to the wide range of applications the demands are strongly varying. A main research topic is the ongoing miniaturization of these drives. Due to their physical working principle conventional drives like solenoid actuators or DC-motors are limited in this issue. Furthermore guidance or gearhead components are mostly needed for providing stiffness or transform the rotational into a linear movement. These components are also subjected to miniaturization restrictions.

SMA actuators are feasible to replace conventional drives in many applications which requiring strokes up to 10 mm and forces up to 100N. Due to the linear working principle applications with linear movement are of special interest. SMA wires as actuating elements open completely new design possibilities and possess to overcome current limitations of conventional drives.

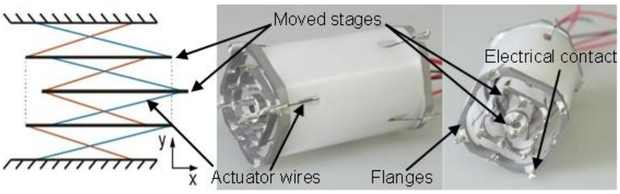

Figure 10 Staged position controlled actuator: principle (left), prototype (right)

In Figure 10 a staged telescope actuator made of SMA wires is shown. The mechanical design principle (Figure 10 left) is based on the antagonistic arrangement described in chapter 2.3. It enables to apply appropriate forces in both actuating directions. Due to the addition of the travel of the three stages this arrangement reduces the cross section in x-direction. Since wires cannot carry transversal loads usually guidance elements are necessary to provide the required stiffness. A differential arrangement and an angular orientation of the wires possess to substitute these by splitting the resulting wire forces into longitudinal and transversal components. As shown in Fig. 10 the SMA elements move the end-effector in x-direction whilst they can further provide stiffness and thus guidance functionality in y-direction. Using a circular arrangement the principle can be enhanced to the third dimension. Figure 10 right shows the prototype of such a staged tubular actuator. The flanges provide fixing the SMA-wires as well as applying the current required for heating the wire.

For accurate positioning of the staged actuator the control concept as described in chapter 3.3 combined with an external position sensor is used. The SMA wires are heated by electrical power that is applied on the flanges of the actuator by controlled current sources. The parameters of the PI-controller are determined using an actuator model. Fig. 11 shows the comparison of simulation and experiment using a stair shaped position reference value. The curves show that there is a high accordance of simulation and measurement for positive but rather higher deviations for negative reference values. This is mainly caused by the complex thermal conditions considering actuator design that are not completely reproducible in the model.

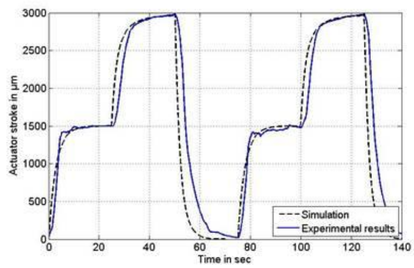

Figure 11 Step response of the staged actuator

The actuator is able to perform a stroke of 5 mm with a force of 50N and achieves frequencies of up to 0.2Hz. The overall weight of the actuator is only 30g. Actually it is planned to use the actuator in a feed drive axis of a micro machining tool machine [6]. However, the actuator principle can be used for other applications too. Further research will focus on miniaturization as well as the development of modularization concepts. Beyond that the design concept will be optimized considering manufacturing and mounting processes.

5 Conclusions and further work

The paper describes the material basics of Shape Memory Alloys as well as the basic design principles considering the mechanical and the control domains. In Chapter 4 two actuator examples are presented. They clarify the outstanding potential of SMA actuators. Even though there are some commercial applications, for example a pneumatic valve for the automotive market [12], a broad market entrance of the technology is not yet achieved. In fact there are still some drawbacks and limitations of the technology. First of all the dynamic behaviour depends on the ambient conditions. Higher ambient temperatures lead to a slower cooling and reduce the reaction time of the actuator. Also the NiTi-alloy is limited to transformation temperatures up to 120°C, thus the maximum operating temperature is limited to values significantly below. Even material research is on the way to provide high temperature alloys, it needs further research until such high temperature alloys are commercial available. Besides the technical limitations there are some other aspects. Up to now there are no standards concerning material properties or design guidelines. Further many industrial engineers got a lack of knowledge of the SMA Technology. So one essential aspect of future work is to establish standards to make the engineers familiar with the SMA Technology

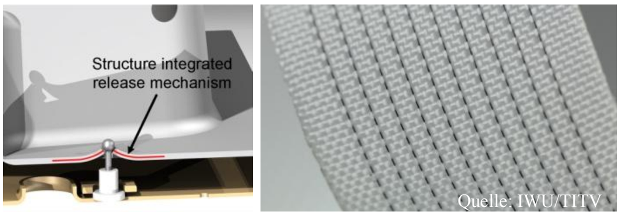

Figure 12 Idea of Structure integrated release actuator (left), textile structure with integrated SMA wire (right)

Another aspect is a bit more visionary. One of the unique properties of SMA is their ability considering integration. Since the energy transformation is done in a simple piece of material it is possible to integrate SMA elements into passive structures like composite materials. Hence, active structures with integrated actuation functionalities can be realized. Figure 12 left shows this vision transferred to the release actuator described in chapter 4.1. It is obvious that all necessary functions like clamping, pre-stressing the actuator and actuating itself has to be implemented into the housing to realize a structure integrated release function. Consequently external actuators become unnecessary. The separation between function and structure does no longer exist. The structure itself realizes the function. This results in a drastic reduction of weight, cross section complexity and finally costs. To achieve this objective further research effort is necessary. This includes the development of design methods and tools like FE-calculation and integration technologies as well as manufacturing technologies. The work has already started. In cooperation with partners Fraunhofer IWU develops textile manufacturing processes for integrating SMA wires in textile structures. A specimen is shown in Figure 12 right. This active textile can be used as core for a composite material. That further enables to design active composite structures.

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