FROM ATTACHED SMA WIRES TO INTEGRATED ACTIVE ELEMENTS – A SMALL STEP?

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1 Abstract
In this publication major challenges occurring during integration of active elements made from shape memory alloys (SMA) in fiber reinforced plastics (FRP) are discussed. Tightly focused experimental tests with a properly chosen setup enable spatially resolved stress and temperature measurement, revealing important material characteristics which have to be considered for the design of integrated active elements. The detwinning process of the martensite during elongation of the SMA elements shows a nucleation, leading to inhomogeneous strain distribution. The measured localized strain and actuation behavior of the active elements and its influence on the performance of hybrid structures is discussed. Also a clamped heating process is investigated to show how stress redistribution affects the processing of hybrid structures during a hot curing process.

2 Introduction
In the field of actuator materials for active composites shape memory alloys (SMA) offer promising performance in terms of available strain and stress. Well established are applications where the actuating SMA element is attached to the structure at certain points, e.g. via crimping, or the SMA element represents the structure itself [1]. The underlying actuator performance with high stresses and a possible strain of several percent matches the performance range of common fiber reinforced plastics like CFRP or GFRP. Especially in wire form a high degree of adaptability of the active elements can be achieved. Similar to FRP, direction and volume content of active filaments in the composite material can be defined individually. Furthermore, the actuation behavior can be precisely adjusted to the application by different pre-strain values [2].

The shape memory alloys show two major effects - pseudoelasticity and shape memory effect. Both are related to the thermoelastic phase transition between the austenitic high temperature phase and the martensitic low temperature phase in the twinned and detwinned state. For actuation purposes the so-called one way shape memory effect, depicted in Fig. 1, is the relevant effect. Starting with an undeformed and stress-free material at a temperature lower than the martensite finish temperature $M_f$, a plastic deformation can be introduced by detwinning the martensitic structure of the material. After passing the stress plateau, the fully detwinned state is reached and during unloading the material shows almost linear elastic behavior. Now the introduced deformation can be restored by heating the material to the high-temperature austenitic phase. During this process, which takes place between austenite start temperature $A_s$ and austenite finish temperature $A_f$, the material contracts to its original shape. This contraction can be used for actuation. When cooling
down to the martensitic phase a load-free one way effect SMA material will show no actuation.

The two way shape memory effect can be understood as a special case of the one way effect. Compared to the one way effect an elongation takes place also during the cooling process, even if there is no load applied, due to a prior introduced preferred orientation of the martensitic structure of the material.
![](explanation.png)

In order to design and manufacture an integrated active composite material the complete integration of the active filaments into the material itself is mandatory. At first sight, it appears possible to apply the well-established manufacturing and handling processes for manufacturing of FRP also to the SMA filaments, when looking at this approach in more detail there are several challenges to overcome.

Two of the main challenges for the development of these new hybrid composites are addressed in this paper:

1) a new boundary condition due to the complete integration of the SMA actuator: every infinitesimal point of the SMA filament is deforming the surrounding composite structure, compared to the discretely attached SMA actuator, which can be seen as a separated system with a single output (Fig. 2) and

2) the problem of activating the temperature driven shape change of the SMA filaments during the curing process of the composite material (Fig. 3).

These challenges are directly linked to the special behavior of the integrated SMA filaments.

The first challenge mentioned above can be explained in more detail by looking at the typical pre-straining process of one way effect SMA. During this pre-straining the maximum achievable strain of the actuating wire is adjusted. Depending on the requirements of the application the introduced strain can typically range from 1 % to 6 %. In the case of active SMA-FRP combinations this maximum strain is typically defined around 2 %. At this point it is necessary to mention, that SMA wires, when used as actuators for various applications, are usually attached only at both end points and the reliable operation is not affected by any inhomogeneous strain distribution along the actuator wire. But being an integral part of the active composite material the SMA wires are attached to the structure in every infinitesimal length, see Fig. 2.

Therefore an inhomogeneous strain distribution in the SMA wire can become critical as it will result in localized stress concentrations, potentially exceeding the adhesive interface strength. In terms of predictability and reliability of the active material this aspect is very important.

Assuming an integrated structure according to Fig. 2 a homogeneous deformation can be achieved, if the stiffness of the structure, the temperature and the applied strain of the actuator are the same at every point. The stiffness of the structure is a result of its specific design and can be assumed homogeneous in this consideration. The temperature distribution depends on the heat flux. For an SMA element activated via joule heating the heat flux can be neglected for short periods of time, leading to a more or less homogeneous temperature distribution. Eventually, the true local strain distribution of the actuator is the aspect which needs to be fully understood, in order to ensure a homogeneous and predictable deformation under the assumed conditions. For this purpose the localized strain potential of the one way effect wire and the two way effect material have to be investigated separately, as the preconditioning procedures for these two types of material are different, resulting in different actuation behavior during operation.
Therefore, the pre-straining process of the one way effect wire requires a closer look. Murasama et al. [4] and Ng et al. [5] reported that a nucleation process takes place during the detwinning of SMA elements. The emerging strain bands and their growth could be measured during the straining of thin SMA sheets and tubes. The above mentioned homogeneity of the strain potential, essential for the integration of SMA wires, can therefore be negatively affected, if this nucleation also takes place during the straining process of thin SMA wires. For the two way effect wire, the homogeneity of strain distribution in the activated state needs to be analyzed to verify the homogeneous strain potential introduced by the manufacturer.

![Fig. 3. Hot curing process and the contradiction to the SMA behavior.](image)

The second challenge is evident when a temperature activated actuator is combined with an FRP in a hot-curing process. To make sure to have sufficient structural material properties, the polymer in the FRP and the adhesive interface between FRP and SMA filaments have to be cured at a temperature which is usually well above the austenite finish temperature $A_F$ of the SMA material. Therefore, the attempt to cure the material in a way to obtain a high enough glass transition temperature $T_G$ for reliable operation of the active composite with its temperature driven actuating elements, ends up in actuating the SMA material itself during processing, as shown in Fig. 3. The requirement of an enhanced $T_G$ of the adhesive is mandatory, as the highest interfacial shear stress in the boundary layer between FRP structure and activated SMA element appears in the heated state, when the strain has to be transferred to the structure. A polymer matrix with its $T_G$ below the $A_F$ temperature of the active element leads to poor mechanical performance in the activated state. This results in a high waste of strain due to the poor stiffness of the adhesive and a high risk of failure due to the poor adhesive strength.

Any hot-curing process above the $A_F$ temperature, however, will initiate the structural phase transition in the SMA material and therefore its actuation. In order to avoid the phase transition and the resulting actuating motion during the manufacturing, precautions must be taken. If a one way actuating SMA material is used, the wire can be clamped during manufacturing [6],[7]. Any change of the wire length is suppressed by the clamping and the occurring stress leads to a raised $A_F$ temperature of the SMA material. With the assumption of monocristalline SMA material and a perfect homogeneous temperature distribution along the activated filament during the curing, clamping is a promising solution. However it has to be verified by experimental tests.

In order to produce hybrid SMA-FRP composites with predictable deformation behavior both challenges have to be mastered. To achieve this goal, an experimental setup for the measuring of the localized strain and temperature distribution along the actuated SMA wire is presented.

4 Experimental

A similar test setup was used for all experiments. First this common setup is described. Then it is discussed in more detail, how it can be used

a) for monitoring the pre-straining process of one way effect wires to evaluate the homogeneity of the introduced strain,

b) to quantify the local strain potential of a two way effect material by measuring the contraction during the heating process and

c) to capture a possibly occurring strain redistribution during a clamped heating of a two way effect wire.

To measure simultaneously the local temperature and strain distribution during the elongation or heating process of a SMA wire, a thermography camera TIM 160 of Micro-Epsilon Messtechnik
GmbH & Co. KG and a video camera (Lumix GH2/Canon EOS 7D) were used and located at the pneumatic clamps of a tensile testing machine 1474 of Zwick GmbH & Co. KG, as shown in Fig. 4. The force and displacement signal of the tensile testing machine were recorded with a QuantumX MX840A of HBM GmbH, as well as the current and the voltage applied to the wire.

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LED light for camera synchronization
Thermography camera
Pneumatic clamps

Fig. 4. Measurement setup at the tensile testing machine with video camera, thermography camera and resistivity measurement connection.

SMA wire
Isolating clamp brackets
Video camera

LED light for camera synchronization

Fig. 5. Thermography and optical picture of the wire.

The electric current was supplied by an HMP4030 Power Source of HAMEG Instruments GmbH, which is connected to the SMA wire using metallic patches in the isolating clamp brackets. As an alternative to one of the isolating clamp brackets, a spring stiffness can be attached to the wire. Depending on the test scenario, the setup described above was used to apply an elongation to the SMA wire / setup a), a heating current during working against stiffness / setup b) or to apply a heating current while the SMA wire is mechanically completely fixed / setup c).

For these investigations SMA wires exhibiting a one way effect were tested (type Alloy M and Alloy H of Memry GmbH with a diameter of 1 mm). For experiments using a two way effect, the wire SmartFlex with 0.5 mm diameter was supplied by SAES Getters S.p.A. All wires were heated up to 100 °C before testing to ensure a reproducible initial condition. Furthermore the wires had a matt black painting on one side to avoid reflections disturbing the thermography measurement, and a pattern of black and white stripes on the other side to enable an optical tracking of different positions. The pattern and the tracking points are shown in Fig. 6. The tested length of the wire was set to 80 mm for a), to 70 mm for b) and to 80 mm for c). The length being observed by thermography and strain measurements, however, is smaller due to the optical boundary conditions.

The three different sample preparations in Fig. 6 belong to three different test configurations:

a) Straining of one way effect wire: The wire is attached to the tensile testing machine on both sides, which strains the wire up to 9 % with a speed of 2 mm/min.

b) Activation of two way effect wire: The wire is clamped on one side by the tensile testing machine and is attached to a spring stiffness on the other. The testing machine is not moving during this test. The force and the total contraction of the wire are recorded by the macro displacement transducers located at the housing of the spring and the load cell of the machine. The contraction of the wire is initiated by a heating current of 3 A.

c) Clamped activation of two way effect wire: The wire is clamped and held in position at both ends by the tensile testing machine during the complete test, suppressing any contraction of the wire while an activating heating current of 3 A is applied.
During all three experiments local strain and temperature distribution was recorded by the optical setup.

![Diagram of SMA wire and camera setup](image)

**5 Results and Discussion**

**5.1 Straining of One Way Effect Wire**

These tests are motivated by noticing a significant deviation and scattering between the signal recorded by the localized macro displacement transducers and the total displacement measured via the load frame of the testing machine in previous straining procedures of SMA one way effect wires.

![Stress-strain curve for Alloy M and Alloy H](image)

**Fig. 7. Stress-strain curves of Alloy M and Alloy H.**

In Fig. 7 stress-strain curves, measured by the load frame of the tensile testing machine and representing the total strain along the wire, are shown for both alloys. The detwinning stress plateau is clearly visible and reaches approx. 6 % strain in the end. For applications, the introduction of an individually adjusted pre-strain value is one of the biggest advantages of these materials. Therefore, the straining process is stopped at a certain strain along the detwinning plateau and the load is removed from the wire.

The following Figs. 8 to 11 give a spatially resolved description of the straining process. In Figs. 8 and 10 for two different materials the development of the local strain, measured optically, is plotted for every x-position along the wire during the straining process, introducing a total strain which is plotted on the third axis. In Figs. 9 and 11 a cross section of the 3-dimensional view in Fig. 8 is shown. The local strain along the wire is depicted for several values of the total strain (shown in different colors). Presenting the data in this way makes it easier to follow the edges, where local strain increases from a very low value (near zero) to the maximum strain value, which is approx. the strain limit of the detwinning stress plateau.
A strongly localized detwinning is visible for both alloy types, ranging for Alloy M between 1 % and 6 % strain and for Alloy H between 1 % and 5 % strain. Below and above these limits the strain distribution is comparatively homogeneous. In-between, the straining process starts at certain positions (Fig. 9 curve “m” / Fig. 11 curve “r”) along the wire and is growing into both directions when the local strain reaches the upper limit (Fig. 9 curve “n” / Fig. 11 curve “o”). This development of strain bands leads to an extremely inhomogeneous distribution of local strain. An SMA wire, strained like that, with a medium strain value of 1 % - 5 % embedded in an FRP structure has an extremely inhomogeneous contraction potential and causes an unpredictable deformation of the hosting structure with local stress concentrations at the edges of the highly strained areas.
The degree of inhomogeneity of strain is quantified in Fig. 12. For every value of the medium strain in a usual stress-strain curve we added the standard deviation of the distribution of local strains. As expected there is only a small deviation from the mean value at the beginning and at the end of the straining process, when the material reaches its upper limit of the detwinning plateau, but large deviations in between. The small deviation values, right at the beginning and at the end, can be attributed to the optical measurement technique. However, the significant rise of the standard deviation is caused by the evolution of the mentioned strain nucleations and the decrease is caused by reaching the upper strain level over the whole wire length.

The local strain distributions found correlate well with the results of thermographic measurements shown in Figs. 13 and 16. The localized increase in temperature can be found at exactly the same positions where the increase in local strain is observed. This can be explained with the release of latent heat stored in the SMA-lattice during the detwinning process. Figs. 14 and 16 depict the temperature distribution along the wire length x for several values of the total applied strain (drawn in different colors), which are the same numerical values as depicted in Figs. 9 and 11. Also the vertical lines indicating the beginning of nucleation of detwinning are shown in both sets of figures simultaneously, providing good evidence for the strong relation between mechanical strain and temperature increase.
The observed strong correlation between nucleation of the detwinning process, which leads to an inhomogeneous strain distribution, and the localized increase in temperature can be explained by combining the observations of Zheng et al. [8], who describes the growing of the nucleation as a domino effect, which is initiated by an additional stress increment acting on the neighbor twins and the findings from Wu et al. [9], who reports the necessary detwinning stress being strongly dependent on temperature. At higher temperatures lower mechanical stress is necessary to detwin the material. Combining this finding with the heat flux of the measured latent heat can also cause a thermally initiated domino effect. Our results depict the domino effect for SMA wires and demonstrate its relevance for their integration in a composite material.

5.2 Activation of Two Way Effect Wire

As discussed previously a homogenous and predictable actuation potential is essential for any application with embedded SMA wires. Therefore, measurements described above are compared with results obtained by actuating a two way effect wire, trained by the manufacturer. To align the wire during actuation it was combined with a relatively weak spring stiffness, giving just enough reaction force to keep the SMA wire well aligned. Fig. 17 shows the total contraction during the heating process, reaching a contraction of 3.1 % at 130 MPa. At the maximum contracted state the whole wire has reached a temperature exceeding 120 °C, except for the small region near the clamping.

The corresponding distribution of local strain for several heating times, ranging from 0 to 5.3 s can be seen in Fig. 18. The lighter the color of the curve the longer is the heating time. A nucleation effect is not evident. The contraction is increasing homogeneously within the observed wire length, except for a significantly smaller contraction at the clamps and a slight gradient over the entire wire length at higher temperatures. Due to the heat flux to the metallic parts of the clamps, the wire
temperature nearby is lowered and the contraction is reduced. At the maximum heating time of 5.3 s the wire directly at the clamp reaches about 90 °C and the temperature increases over the next 3.75 mm up to 120 °C. Despite of the slight gradient in the strain distribution, a homogenous contraction can be achieved, enabling a predictable deformation behavior of hybrid SMA-FRP structures without critical local stress concentrations over the wire length.

5.3 Clamped Activation of Two Way Effect Wire

To achieve a homogeneous contraction of the SmartFlex wire in the hybrid structure, the manufacturing process must not affect the behavior afterwards. Therefore, a clamped heating process is now investigated. Only the heating process is of interest, as the hybrid structure is cured at an elevated temperature and the wire will already be embedded in a cured resin during the cooling process.

The results in Fig. 19 clearly show two simultaneous processes going on during heating. The contraction of the major part of the wire is enabled by an elongation of the colder part near the clamping. The contraction with values below 0.5% is relatively small, but as the major part proceeds to contract, the colder areas at the edges of the wire with a width of about 7 mm are significantly elongated with values of up to 4%. The actuation behavior of these elongated parts is definitely affected or destroyed.

The situation presented is the result of a relatively fast heating process, which takes about 8 s, and thermal inert clamps. The situation could be improved by using nonmetallic clamps, but compared to the heating process of a composite manufacturing process the Joule heating is a relatively homogeneous heating process. The heating during a conventional manufacturing process would be much slower and in addition be affected by a variety of boundary conditions such as the thermal capacity and thermal conductivity of mold and structure, the heating method, heating speed and the wire clamps. In practice it will hardly be possible to ensure a totally homogeneous heating and to avoid simultaneous elongation and contraction effects. Therefore presented effect needs to be further investigated, in order to define maximum tolerable temperature differences to suppress a self-straining or to ensure small strain redistribution, not negatively affecting the actuation behavior.

6 Conclusions

The experimental results shown so far enable to deduce guidelines for future application and illustrate further aspects, which need to be investigated to achieve a reliable and reproducible active SMA-FKV hybrid composite.

- A nucleation of the detwinning process takes place during the pre-straining of one way effect SMA wires and leads to an
extremely inhomogeneous distribution of local strain at mean values of total strain below the pseudoplastic strain limit. As long as the nucleation cannot be suppressed, only totally detwinned SMA wire provides a predictable and reliable behavior for integration purposes.

- The nucleation of detwinned areas and their growth is the result of a domino effect, which can be initiated by stress increments and/or by a heat flux of the latent heat, as the results suggest. How the nucleation could be suppressed needs to be further investigated, as the free choice of a suitable pre-strain is an important degree of freedom in the design of active hybrid composites.

- During the heating and the contraction of a commercially available trained two-way effect SMA wire no nucleation was found. The phase transition between martensite and austenite is homogeneous as long as the temperature is homogeneous; which needs to be considered in applications. Apart from that, the wires are well suited for the integration in FRP.

- The results of the clamped activation test clearly show that clamping does not necessarily lead to a complete suppression of all contractions. Colder regions, in our case the areas near the clamping, can be elongated by the warmer portion of the wire. Further investigations of the temperature sensitivity of this effect are necessary to decide if a clamped hot curing is a promising manufacturing process. Knowing the temperature difference allowed, to avoid the presented strain redistribution is the key for the SMA integration with conventional curing processes for FRP.

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References


