CHARACTERIZATION OF THE LOAD TRANSFER BETWEEN FIBER REINFORCED COMPOSITES AND SHAPE MEMORY ALLOYS FOR ACTIVE HYBRID STRUCTURES

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Abstract
For actuation purposes active hybrid structures made of fiber reinforced polymers (FRP) and shape memory alloys (SMA) can provide substantial savings concerning weight, space and cost. They can also enable new functions. But to use the complete actuation performance of the active SMA wires the load transfer between these wires and the FRP structure is the most critical point. For the testing of this load transfer as well as its improvement there is still no satisfactory solution. Within this contribution we present new experimental data and compare different possibilities to improve the load transfer. We also show an approved experimental set up for a pull-out test with optical stress measurement via photo elasticity for an exact measurement of the transferred load leading to primary failure of the interface which leads to a better forecast of the transferred load of the specimen. We also carry out typical pull-out tests for a comparison of the results.

1. Introduction

For actuation purposes active hybrid structures, which show a bending behavior by activation of shape memory alloys (SMA) integrated in fiber reinforced polymers (FRP), can provide substantial savings concerning weight, space and cost (see Fig. 1) and also enable new functions. SMA show an outstanding actuation performance in terms of achievable stress (up to 600 MPa) and strain (up to 6 %). This performance matches the mechanical behavior of FRP and, especially with SMA wires, a high degree of adaptability of the active elements can be achieved. Similar to FRP the direction and volume content of active filaments in the composite material can be defined individually and tailored to the application [1]. First aerodynamic applications were shown in [2,3]. The active vortex generators [3] demonstrate the possibilities of such hybrid composites because a realization of such a high number of active elements in the wing surface of an aircraft is almost impossible with standard actuators.
To allow for the complete actuation performance of the active SMA wires the load transfer between the SMA wires and the FRP structure is the critical point. If the shear stress between the active SMA wire and the passive FRP structure exceeds a critical value, the interface of the hybrid structure will fail. As shown in [4,5] the shear stress in the interface between SMA and FRP of the hybrid structure is not homogenous. As the shear stress in the interface between SMA and FRP is the first derivative of the longitudinal stiffness of the specimen with respect to this direction, a stress concentration at the two ends of the specimen occurs. This means that for the hybrid composite the load transfer is concentrated in these outer areas, at the two ends of the composite material (see. Fig. 2 a).
Several authors investigated methods to improve the load transfer between these two materials by chemical and mechanical modification of the wire surface or the use of coupling agents [6-9]. A few

authors also investigated an improvement of the load transfer by mechanical interlocking [10]. Typically the measurement of the transferable load between SMA and surrounding matrix is done by pull-out tests. But the inhomogeneous elongation of shape memory alloys under tensile load due to nucleation of detwinning areas in combination with the stress concentration in a small load transfer area at the wire entry area lead to poor comparability between the several works (see Fig. 2 b).

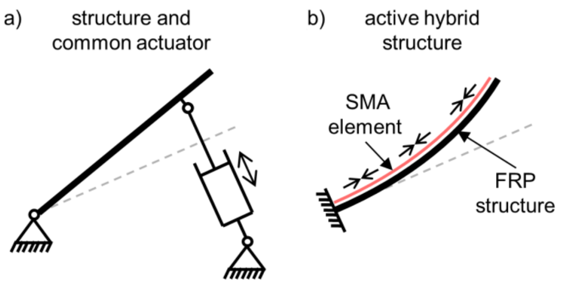

Figure 1. Comparison of actuation principles: (a) mechanical system and common actuator, (b) active hybrid structure with integrated solid state actuator (e.g. SMA).

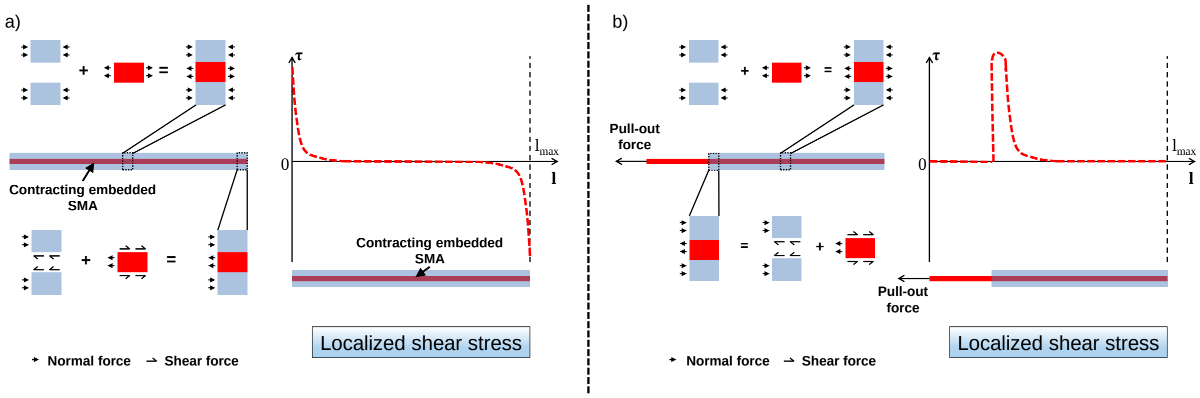

Figure 2. Shear stress distribution in: (a) active hybrid composites, (b) and pull-out sample.

In this contribution a comparison between three methods for characterization of the transferable load between SMA wires and FRP is presented: 1) state of the art pull-out tests, 2) pull-out tests with varying ambient temperature, 3) pull-out tests with thermal activated contraction of pre-strained SMA wires. An optical stress measurement via photo elasticity for the pull-out tests shows the localized stress distribution within the matrix material. A comparison between different methods for the improvement of the load transfer especially by mechanical interlocking is also shown within this contribution.

The results of the different measurement methods show that a qualitative measurement of the transferable load via pull-out forces is possible. But the results of the optical stress measurement clearly reveal that a quantitative determination of the mechanical stress in the interface is almost impossible because of the undefined surface area of the interface which contributes to the load transfer. The optical stress measurement coupled with the load measurement also suggests that the maximum measured load is only reached clearly after the primary failure of the interface between SMA and matrix, most possibly due to a reduction of the stress concentration due to frictional effects.

2. Experimental

2.1. Test setup

The pull-out tests were carried out with a tensile testing machine Zwick RetroLine 10 kN. For the tests a special sample holder was manufactured which ensures a good positioning of the samples (no lateral forces) and also a good support of the wire surrounding matrix. Fig. 3 shows a simplified sketch as well as a picture of the complete pull-out setup. With this the samples were fixed in the tensile testing machine. The free end of the SMA wire was clamped with a pneumatic clamp and pull-out forces were introduced to this end of the SMA wire.

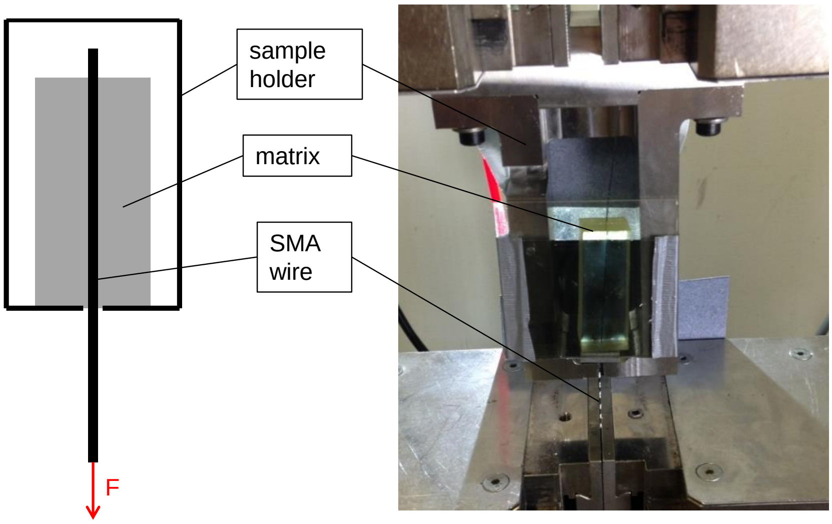

Figure 3. Simplified sketch and picture of experimental setup for pull-out tests.

For a qualitative measurement of the internal stresses in the interface optical stress measurement, using polarization filters fixed in front of and behind the samples, was carried out. A high speed camera MotionXtra N4 from Imaging Solutions GmbH was used for capturing of the images for optical stress measurement. The pre-load of the samples was defined with 5 N. For the tests two different strain rates were used: 1) 25 %/min, which corresponds to a typical activation speed for SMA wires in active hybrid composites; 2) 1000 %/min, which was the maximum strain rate of the tensile testing machine. At this strain rate nucleation of the free part during detwinning of the SMA wires should be suppressed, leading to a more homogeneous stress-strain characteristic in the SMA and an instantaneous increase of shear stress between SMA and polymer matrix at the wire entrance into the matrix [11]. The influence of the strain rate to the detwinning of the embedded part of the wire is probably small due to the obstruction of free elongation by the matrix. But an increase of the strain rate will also lead to a more brittle material behavior of the matrix due to strain hardening. The tests were carried out at room temperature (RT). Further tests at 100 °C were carried out to determine the influence of higher temperatures, which leads to a softening of the matrix as well as a phase transformation of the SMA wires (martensite at RT, austenite at 100 °C).
For the pull-out tests with thermal activated contraction of the SMA wires the wires were pre-strained to 3.9 % (4.5 % before relief of strain) before they were embedded in the matrix. For these tests the traverse of the tensile testing machine was fixed after reaching the pre-load. The wires were heated via joule heating with a current of 3 A.

2.2. Materials and sample preparation

For the tests we used NiTi wires Alloy M of Memry GmbH and as surrounding matrix epoxy resin Araldite LY 5052 in combination with the curing agent Aradur 5052 from Huntsman Advanced Materials, cured at room temperature. The essential material data are summarized in Table 1 and 2.

Table 1. Material data of used NiTi wires (A_s: austenite start temperature, A_f: austenite finish temp).

E_M	E_A	A_s	A_f	d
25-40 GPa	70-80 GPa	54 °C	69 °C	0.5 mm

Table 2. Material data of used epoxy matrix [12].

Curing conditions	E	σ_M	ε_b	T_g
RT	3.35-3.55 GPa	50-70 MPa	1.5-2.5 %	~65 °C
RT + 1 h at 100 °C				~ 120 °C

For the preparation of the samples the SMA wires were clamped in a frame to ensure a good positioning of the wires in the pull-out samples. The fixed wires were positioned in a mold and afterwards the matrix material was filled in the mold. The samples cured for at least 7 days at room temperature. The samples for the characterization of the influence of the temperature were afterwards tempered at 100 °C for 1 h. Four kinds of samples were manufactured for the characterization of different load transfer mechanisms (see Fig. 4): 1) as delivered wires, 2) handsanded wires, 3) wires with a crimp sleeve, 4) wires with spot welded anchor wire.

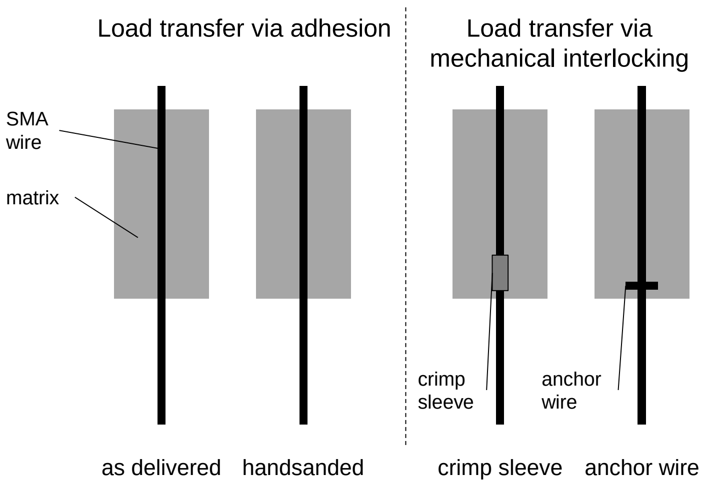

Figure 4. Different types of load transfer mechanisms for the tested samples.

3. Results

3.1. State of the art pull-out tests with variation of strain-rate

Fig. 5 and Fig. 6 show the results of the pull-out tests for samples of the types “as delivered” and “anchor wire” at a strain rate of 25 %/min. The optical stress measurement shows for both tests a stress concentration at the wire entrance, which is caused by the increasing step in stiffness seen by the SMA-wire when its surrounding changes from "air" to "epoxy-matrix". From Fig. 5 it can be found, that the movement of the stress concentration inwards the sample, which occurs due to an advancing failure of the interface, correlates to several force peaks in the force-strain diagram. Fig. 6 shows that this correlation does not exist in every case. Despite a failure of the interface (see Fig. 6, image 1), which is clearly visible with the optical stress measurement, no drop of the force is apparent in the force strain diagram at the corresponding position. Without the optical measurement the pull-out force for failure would be assumed with a significant higher value than the real value (150 N instead of 60 N). These results show the importance of the optical stress measurement for the analysis of pull-out forces of SMA wires embedded in a polymer matrix.

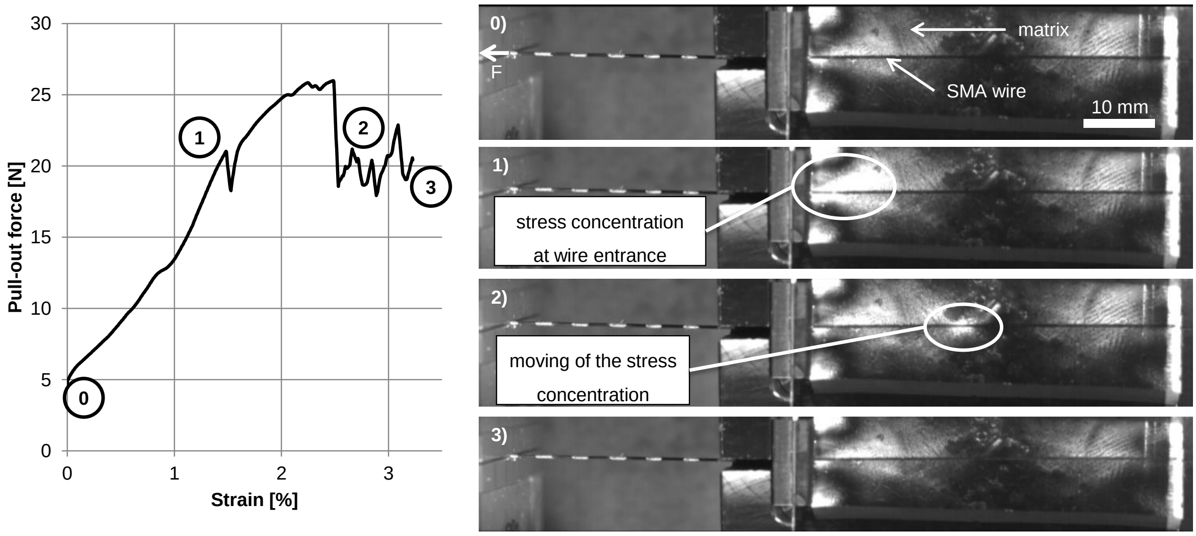

Figure 5. Results of pull-out test for as delivered wire and strain rate of 25 %/mm. The numbers along the force strain characteristic indicate the positions where the images were taken.

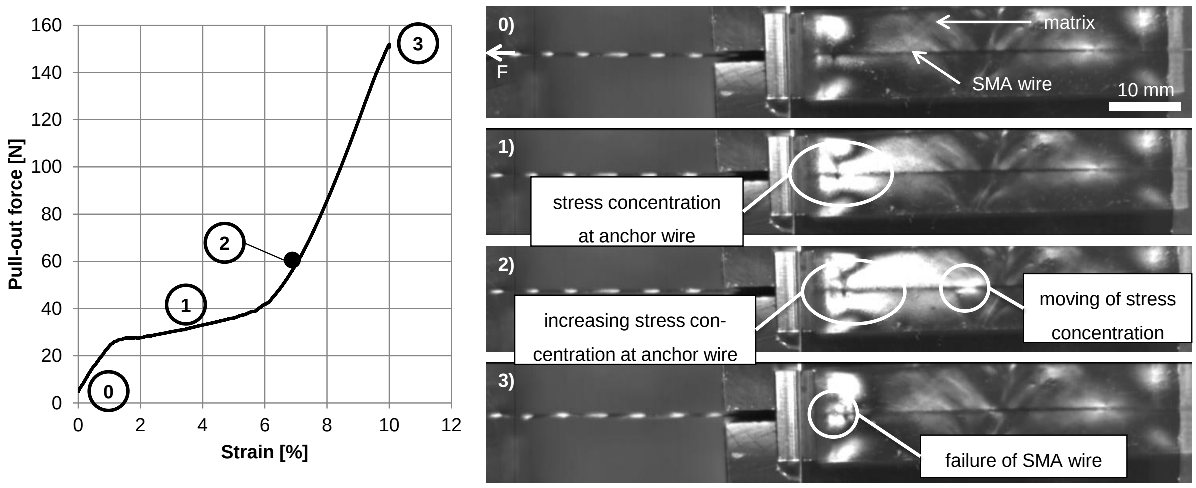

Figure 6. Results of pull-out test for a sample with anchor wire and strain rate of 25 %/mm. The numbers along the force strain characteristic indicate the positions where the images were taken.

Fig. 7 reveals that an increase of the strain rate leads to smaller pull-out forces due to the strain hardening of the matrix. To understand the influence of increasing strain rate affected by the SMA behavior in detail, especially the homogenization of the detwinning, it is important to know the failure is caused either on strain based failure or stress based failure of the interface. Also it is visible, that for “as delivered” wires the pull-out force is in the same range as the force of the detwinning plateau. This means that two options a possible: failure of the interface or detwinning of the free wire. An investigation of these topics is still outstanding. Fig. 7 also shows that a mechanical interlocking improves the load transfer behavior significant (pull-out force: 20 N vs. 80 N), while the modification of the wire surface by handsanding only leads to small improvement. On the other hand it is visible that the spot welding of a SMA anchor wire leads to poor reproducibility of the samples due to a change in the microstructure of the SMA wire due to impurities and oxide formation during the welding process. In contrast to this the use of crimp sleeves leads to good reproducibility and a considerable improvement of the load transfer in comparison to as delivered or handsanded wires (20 N vs. 40 N).

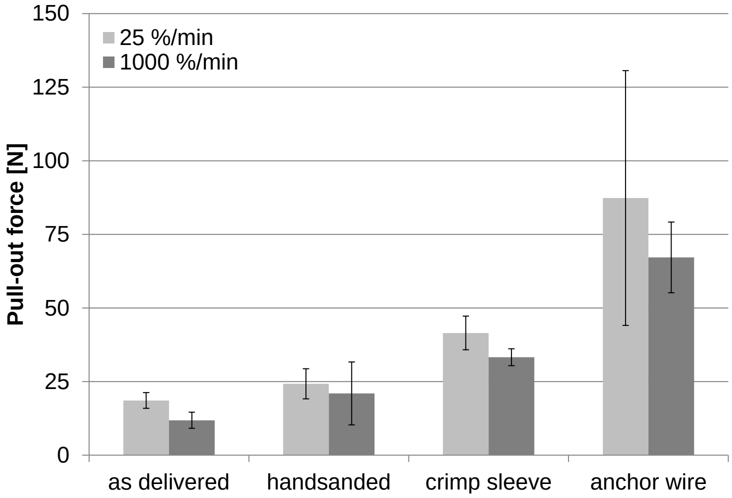

Figure 7. Pull-out forces for different strain rates and load transfer mechanisms.

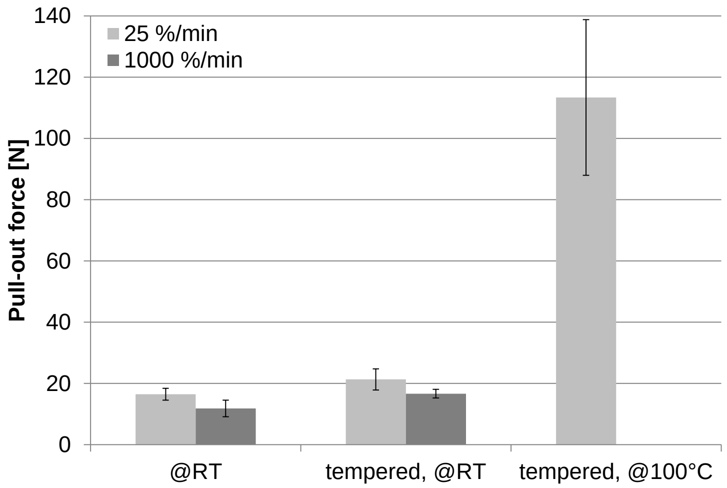

Figure 8. Pull-out forces for different strain rates and temperatures.

3.2. Pull-out test with a variation in ambient temperature

Fig. 8 shows that a tempering step of 1 h at 100 °C after curing of the matrix at RT has almost no influence on the measured pull-out forces. But it also shows that testing at 100 °C, which is almost T_g of the tempered matrix and also above A_f of the SMA wire, leads to significant higher pull-out forces (20 N vs. 110 N). This could be an effect of the softening of the matrix at T_g but also be influenced by the higher tensile modulus of the SMA wire, which means that for the same force level the strain in the wire and therefore also in the interface is reduced. Effects of strain induced martensite formation could be precluded due to a transformation stress of used SMA wires of 700 MPa, which corresponds to a force of about 135 N. This means that for the measured forces only elastic deformation of the SMA wire is expected.

3.3. Pull-out tests with thermal activation of pre-strained SMA wires

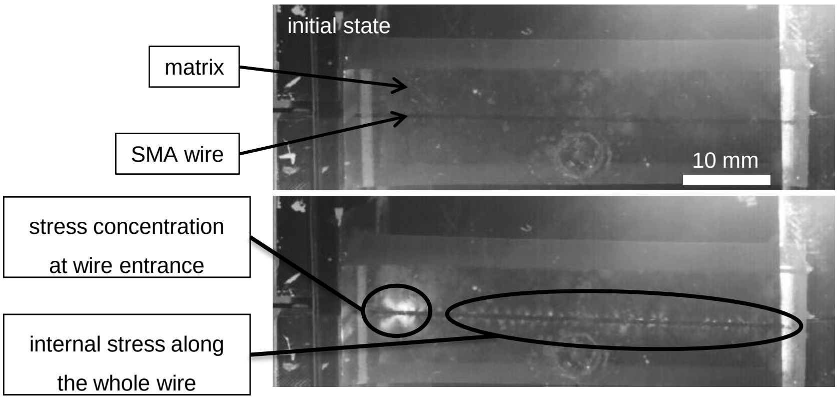

Figure 9. Internal stress distribution in sample for thermal activated pre-strained wires.

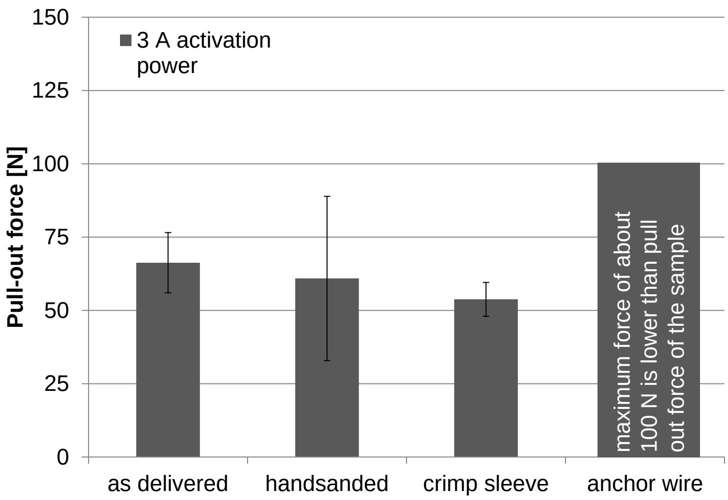

Figure 10 Pull-out forces for thermal activated pre-strained wires.

Fig. 9 shows the optical stress measurement of a sample for a thermally activated pre-strained SMA wire. The difference in the stress distribution in comparison to state of the art pull-out tests is clearly visible. The contraction of the not embedded part of the wire accumulates to an enhanced stress concentration at the wire entrance comparable to conventional pull-out tests but the contraction of the embedded part of the wire generates an internal stress along the whole embedded wire surface. Also the thermal activation may influence the temperature of the interface and the surrounding matrix, so that this area is probably near T_g. A detailed investigation of the heat transfer and the temperature distribution in the pull-out samples is still outstanding. A notable influence to measured pull-out forces can be seen with a big increase compared to state of the art pull-out tests. For the samples with anchor wire it was not possible to generate a failure of the interface because the maximum forces generated by wire contraction are limited to about 100 N (500 MPa stress in the SMA wire). This relates to the effect that for a wire working against high stiffness the maximum contraction of the wire is limited to about 1.5 %. The temperature measurement showed temperatures of more than 150 °C at the not embedded wire surface, which is significantly above the austenite finish temperature of the material of about 70 °C.

4. Conclusions

In conclusion the pull-out tests we showed within this contribution illustrated that:

- Mechanical interlocking increases the pull-out forces by about 400 % (compared to adhesion).
- An increase of the strain rate leads to a decrease of pull-out forces because of the strain hardening of the matrix and with this also of the interface.
- Optical stress measurement shows that a failure of the interface is not necessarily visible in the force strain diagram, which leads to too high resulting pull-out forces.
- An increase of the surrounding temperature to almost T_g of the matrix improves the measured pull-out forces by about 500 %.
- Thermal activation of pre-strained SMA wires leads to higher pull-out forces compared to state of the art tests but also to internal stresses along the whole embedded wire surface.

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