4D-PRINTING OF HYBRID COMPOSITES INTEGRATION OF SHAPE MEMORY ALLOY WIRES ON MATERIAL LEVEL USING SLA PRINTING TECHNIQUE

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ABSTRACT

In this work, we present first results on a new approach for the full integration of shape memory alloy (SMA) wires into fibre-plastic composites on material level. By combining textile technology and additive manufacturing methods we took advantage of the stereo lithography printing process (SLA) which enabled the formation of structures with graded stiffness and the usage of UV curing material at low processing temperatures, to integrate a hybrid glass fibre-SMA textile preform into a morphing composite structure, a so called shape memory alloy hybrid composites (SMAHC).

This work also includes a first characterization of the shape deflection and actuation capability of the component as well as an assessment of the heat distribution inside the material resulting from electric activation.

1 INTRODUCTION

The replacement of conventional actuators such as electric or hydraulic motors and mechanisms in aerodynamic applications in the automotive industry or in aeronautics with such shape memory alloy hybrid composites (SMAHC) is vastly advantageous, because of the reduced complexity and savings in weight and installation space [1]. Typical applications are aerodynamic components such as wing profiles or rear spoilers [2]–[4]. An evaluation of the applicability of active shape memory alloy hybrid composite technology for achieving an adaptive airfoil trailing edge is done in [5]. The study focuses on a demonstrator component that highlights the potential of this concept as an exceptionally lightweight alternative for a morphing trailing edge. Experimental investigations of the demonstrator are conducted in a laboratory setting.

Additive manufacturing, commonly referred to as 3D printing, has gained significant popularity in the manufacturing industry owing to its versatility, cost-effectiveness, and rapid prototyping capabilities [6]. The integration of shape-memory materials (SMMs) with 3D printing has enabled the development of dynamic and adaptive products that can respond to physical, chemical, or biological stimuli. These innovative structures fall under the category of 4D-printing, which exhibit changes in shape and properties over time. 4D printing delivers wide-ranging applications in sectors such as healthcare, space exploration, textile manufacturing, soft robotics, defence, sports, aerospace, and automotive industries [7]. Main advantage of using 3D printing for the realization of SMAHC is the possibility to tailor the stiffness of the component to allow for large deflections of the structure, being induced by the SMA wires, while simultaneously withstanding static or dynamic loads.

The aim of this paper is to present a new method for the fabrication of SMAHC using the 3D stereolithography process. For the direct integration of Shape Memory Alloy into plastic matrices, the matrix material must have sufficient flexibility, as the SMA's transformation process can undergo an elongation of up to 8%. Furthermore, it must be ensured that the process temperature of the selected manufacturing method is below the austenite start temperature A_f in order to exclude the possibility of the SMA being activated during the manufacturing process. For this reason, the 3D stereolithigraphy process was chosen. The following chapters explain the manufacturing process of such a SMAHC and its activation under laboratory conditions.

2 MATERIALS

Shape Memory Alloy

The developed SMAHC is using nickel (Ni) and titanium (Ti)-based shape memory alloy wires (Smart-Flex) from SAES Getters with a diameter of 0.5 mm. The material parameters are listed in Table 1.

Table 1: Material properties of the Smart-Flex Wire by SAES Getters

Names	Sym.	Unit	Val.
Austenite start temperature[1]	A_s	$°C$	50
Austenite finish temperature[1]	A_f	$°C$	80
Young's Modulus martensite[2]	E_M	GPa	45
Young's Modulus austenite[2]	E_A	GPa	42
Maximum recoverable strain[3]	ϵ_L	%	4

Characterization methods:
[1] DSC characterization according to [5], [6], [7]
[2] Monotonic loading according to [8], [9]
[3] Thermoelastic properties characterization according to [9]

Resin

Two different resin systems were used for the manufacturing of the SMAHC. For the elastic layer in which the glass fibre SMA fabric is integrated, the Elastic 50A photopolymer from Formlabs was used. The material properties are listed in Table 2.

Table 2: Material properties of Formlabs Elastic 50A resin

Names	Sym.	Unit	Val.
Elongation at break (post cured)	ε_b	%	160
Shore Hardness (post cured)			50A
Tensile strength (post cured)	R_M	MPa	3.32
Wavelength	λ	nm	405

Anycubic Black Resin was used for the lower base-layer. The material properties are listed in Table 3.

Table 3: Material properties of Anycubic Black resin

Names	Sym.	Unit	Val.
Elongation at break (post cured)	ε_b	%	8 – 12
Shore Hardness (post cured)			82D
Tensile strength (post cured)	E_M	MPa	36-45
Wavelength	λ	nm	405

Fabric

The glass fibre scrim into which the SMA is woven has a basis weight of 300$\frac{g}{m^2}$

3 MANUFACTURING

Stereolithography

Stereolithography is a 3D printing process in which a liquid photopolymer resin is cured layer by layer using a laser beam or LCD display. In the Anycubic 3D printer, the resin is exposed through an ultraviolet light source, instead of using a projector. The UV light needed to solidify each layer is emitted from an array of LEDs that shine through an LCD screen, which serves as a mask to selectively reveal the pixels required for the current layer while blocking out the rest (Figure 1). This causes the individual pixels on the underside of the stamp to polymerize where the light hits them, while the resin remains liquid in the unexposed areas.

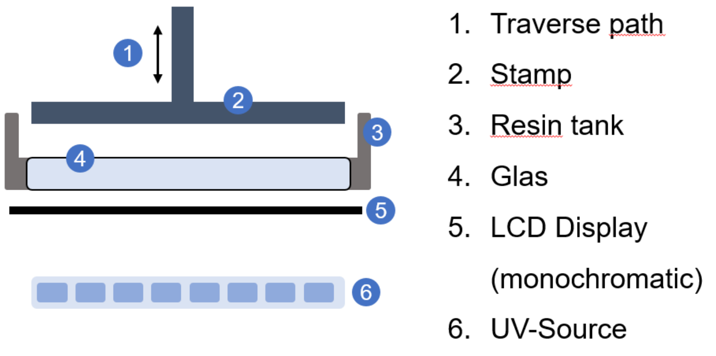

Figure 1: Work principle of the 3D SLA printer by Anycubic

After a layer has hardened, the stamp is raised by the height of the next layer and the process is repeated. This process is carried out layer by layer until the entire model is completed. After the printing process is done, the build plate with the finished 3D model is removed from the printer. The model is then cleaned of excess resin and cured in a UV light source to fully stabilise and harden it.

SMAHC concept

Figure 2 shows the concept of the SMAHC. The first layer is the actuator-layer, which contains the glass fibre fabric into which the SMA is woven. Underneath the actuator layer are several elastic intermediate layers, which enable load transfer to the underlying base laminate layer. The base laminate layer is made of a stiff material so that the resetting into initial position of the SMAHC after deactivation can be guaranteed.

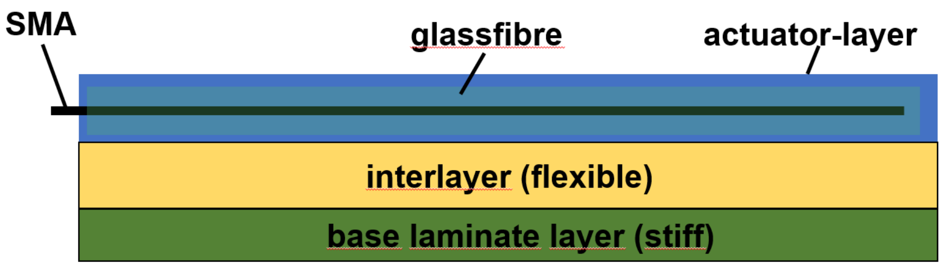

Figure 2: SMAHC concept with the different layers

The manufacturing process of the SMAHC comprises five steps.

Step 1: Preparing the SMA wire

In order to be able to call up the one-way shape memory effect of the wire, it must first be pre-stretched. To do this, the wire was stretched by 4% using a universal testing machine (ZwickRoell 1445). This causes the martensitic crystal lattice, which is originally in the twinned state, to detwin in order to retrieve the shape memory effect. Furthermore, the wire was cleaned with isopropanol to ensure the best possible adhesion to the matrix material.

Step 2: Deactivation of the meander points

To prevent the pre-stretched SMA wire from being activated in the meander-shaped anchorage points, which would lead to a large deformation in the anchorage, the shape memory effect must be deactivated in these points. To do this, a current of 3 A is applied to the wire at the desired point with the help of electrodes, so that the wire heats up and a structural transformation takes place. In order to ensure that the wire was exposed to the desired temperature (above the austenite finish temperature), the process was examined using a thermal camera (micro epsilon, TIM 640). Since the shape memory alloy used is a one-way effect alloy, further activation in the anchor points is no longer possible.

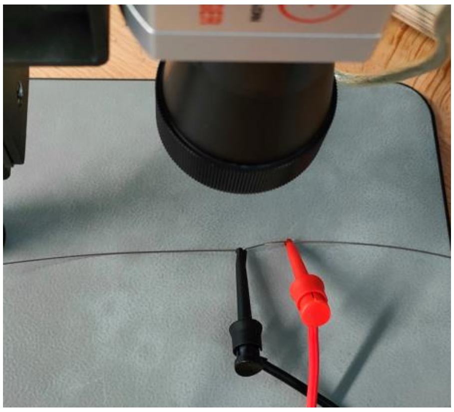

Figure 3: Deactivation of the anchor-points

Step 3: Integration of the wires into the glass fibre fabric

For better anchoring of the wires in the plastic matrix, the SMA wire was woven into the glass fibre fabric by hand. Here, the SMA wire serves as the weft thread, the thread bundles of the glass fibre fabric serve as warp threads. At the meander-shaped anchoring points, the SMA wire was sewn together with the help of another glass fibre yarn.

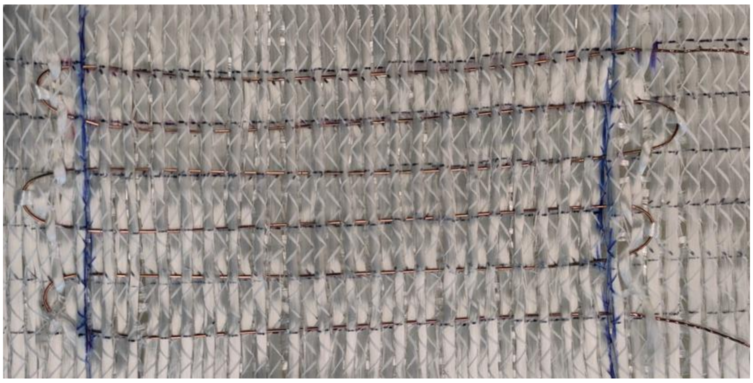

Figure 4: Glasfibre-SMA woven fabric

Step 4: SLA printing

First, the fibreglass SMA fabric is attached to the underside of the stamp so that it can be accurately positioned for later 3D printing. Then the stamp is placed in the resin bath so that the fabric structure is completely impregnated with the resin. The elastic material "Elastic 50A" from Formlabs is used to embed the glass fibre SMA fabric. After about half an hour, the actual printing process is started. For this purpose, in a first step, the glass fibre SMA fabric is exposed for a duration of ten minutes to create a base layer with a thickness of 2.5 mm. Subsequently, further layers with a thickness of 2.5 mm are applied with a curing duration of ten minutes. Finally, the base laminate layer is applied. This is a stiffer layer that allows the SMAHC to reset. The stiff base laminate layer consists of the photopolymer "Anycubic Black Resin" from Anycubic. For this purpose, a 1 mm thick layer was applied to the SMAHC with an exposure time of one minute.

Step 5: Post-curing

After the last layer of SMAHC has been completed and the printing process is finished, the stamp with the component attached is removed and cleaned with isopropanol using a washing device. This removes any excess resin residue. After the component is completely dry, it is again illuminated with UV light in a post-curing station, so that post-curing of the component takes place in order to achieve the material characteristics specified in the data sheet. After UV post-curing, the SMAHC is post-cured in an oven at 45°C for approximately 30 minutes.

The SMAHC produced has a length of approx. 160 mm with a width of approx. 100 mm and a component thickness of approx. 9 mm (Figure 5).

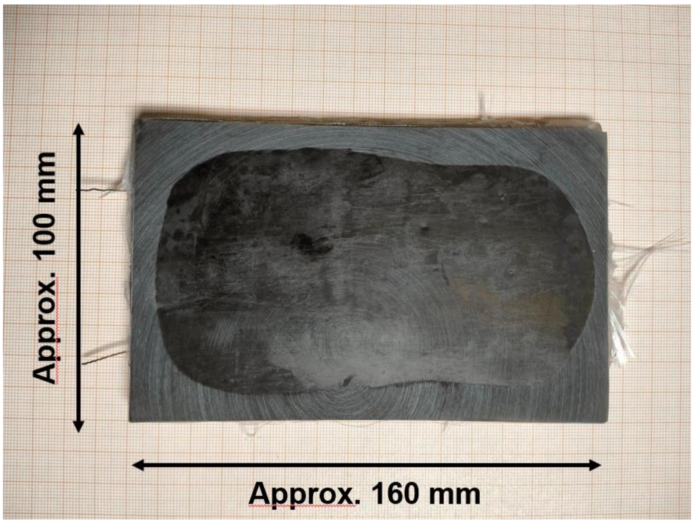

Figure 5: Manufactured SMAHC

4 TESTING AND RESULTS

To activate the SMA in the SMAHC through thermal means, a laboratory power supply unit (Delta Electronica ES 030-10) was utilized. The unit had a maximum capacity of 32V, but a preliminary experiment determined that 12 V was sufficient for maximum deformation. At this voltage level, an electrical current of 4 A was established in the SMA. After shutting down the electric power supply the cooling of the SMAHC was established by an ambient temperature of 23°C. After the SMAHC had cooled down completely, the next heating cycle was started. Ten cycles were completed in a first trial. For the first experiment, the tip deflection was measured with the help of a measuring rod. A tip deflection of up to 50 mm could be measured. The process was observed by a thermocamera (TIM 640 form Micro-Epsilon). The maximum surface temperature measured was approximately 64°C (Figure 6).

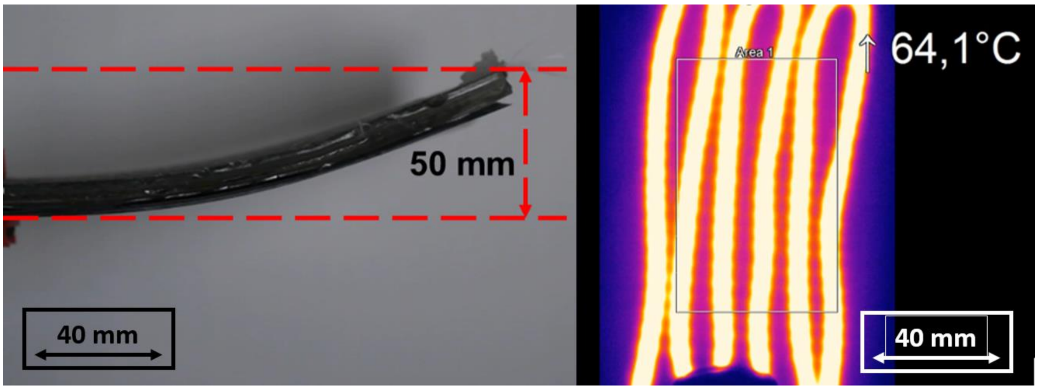

Figure 6: full deflection of the SMAHC (left), thermocamera record at full activation of SMAHC (right)

5 CONCLUSIONS AND FUTURE OUTLOOK

Overall, the results of the first trial to manufacture a Shape Memory Alloy Hybrid Composite (SMAHC) using the stereolithography process reveal some promising properties. The anchoring of the SMA in the glass fibre fabric during activation and the strong adhesion between the two plastic matrices are positive aspects. The stability of the SMAHC under a load of 10 cycles is also a promising result. Since a maximum temperature of up to 64°C could only be measured on the surface of the SMAHC, but one must assume that the temperatures inside must be much higher. This represents a challenge for the use of photopolymers. Further research is needed to evaluate the advantages and disadvantages of this technology compared to other manufacturing methods and to determine the applicability of the process in different application areas. In future work, optimisation of the interlayer must be undertaken. The interlayer, which is the layer between the actuator layer and the base-laminate-layer, must have sufficient stiffness so that the SMAHC is rigid enough to support its dead load, whereas sufficient flexibility of the interlayer will allow for the highest possible deflection of the SMAHC.

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