Shape-variable adaptive fiber-reinforced plastics based on shape memory alloy hybrid yarns

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Abstract In the transport and industrial sectors, moving parts and kinematics play an important role. In this context, weight savings and a reduced number of joints of moving parts are essential factors, enabling lowered fuel consumption and precise dynamic movements of machine parts. Hence, single-axis and intrinsic adaptive fiber-reinforced plastic (FRP) components with structurally integrated actuators can replace conventional moving parts. Thus, this paper aims at presenting shape-variable, adaptive FRP based on shape memory alloy (SMA) hybrid yarns. In order to protect the matrix from direct contact with SMA, to ensure free and even mobility of SMA in FRP, and to fully exploit the deformation capability of SMA and therefore the adaption potential of the entire FRP structure, wire-shaped SMA was converted into textile-based actuators in a core-sheath structure. The functionalized preforms were developed by means of weaving technology. The SMA hybrid yarn was introduced into the woven fabric structure in the warp direction. Subsequently, the functionalized preforms were infused. The adaptive FRP were characterized in terms of their deformation behavior with fully and partially sheathed SMA in lengths of 240 mm and 120 mm, respectively. Results revealed that adaptive FRP with fully sheathed SMA deform stronger than those with partially sheathed SMA.

***Keywords*—Adaptive fiber-reinforced plastics, shape memory alloys, weaving, friction spinning technology.**

I. Introduction

THE importance of fiber-reinforced plastics (FRP) for different novel products in automobile, aerospace or wind energy has been growing steadily in recent years [1]. The integration of functional materials into the reinforcement fabrics of FRP poses a breakthrough for the development of different innovative products for lightweight applications. Electroactive materials, magnetostrictive materials, piezo electric materials, bimetals, shape memory polymers and shape memory alloys (SMA) are examples of functional materials being promising candidates for actuators in FRP. However, SMA are more suitable than other functional materials due to their higher energy density (10^7 J/m^3) [2]. Moreover, SMA are commercially available in wire form, which is one of the most important criteria for the textile technical integration of SMA into reinforced fabrics.

SMA is a material that remembers its original shape after being heated over its phase transformation temperature [3]. The thermally induced shape-memory effect (SME) is activated by Joule heating. Below the transformation temperature, the twinned martensite alloy is deformed plastically without damaging its crystalline structure. By the thermal induced activation of the detwinned SMA above its transformation temperature, a phase change into an austenite state is included, accompanied by the regression of deformation. As a result of cooling the SMA to temperatures below the transformation temperature, a phase transition into martensite and thus into the initial state is triggered. This phenomenon is illustrated in Fig. 1.

Different alloys are commercially available, which can be used as SMA, such as copper-zinc-aluminum (CuZnAl), copper-aluminum-nickel (CuAlNi) or nickel-titanium (NiTi). However, NiTi-based SMA is preferable for most FRP applications due to its higher elongation at break of 12.5% and maximum strain recovery of 8% [4].

The development of adaptive FRP with textile-technically integrated SMA into reinforced fabrics has been expanded steadily in recent years [5-10]. However, this research project presents the development of adaptive FRP with SMA hybrid yarn (SMA-HY), which was structurally integrated into textile-reinforced fabrics by means of weaving technology. The developed adaptive FRP were electro-mechanically characterized based on fully and partially sheathed SMA.

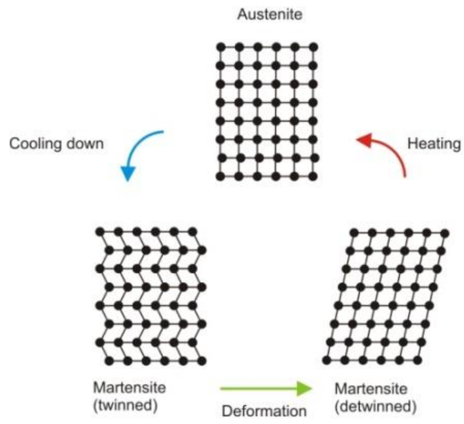

Fig. 1. Schematic representation of shape memory effect (SME) [5].

II. Materials and methods

A. Materials

In this research project, E-glass rovings type EC17-1200-350 (PD Glasseiden GmbH, Germany) were used for the formation of a base structure. E-glass was selected as this type of glass fibers (GF) is most frequently used for FRP applications due to its favorable mechanical properties, good processability and beneficial price-performance ratio compared to other GF.

A commercially available Alloy H ox. sa. (Memry GmbH, Germany) type of SMA was used for the functionalization of the adaptive preform. The basic properties of the SMA are listed in Table 1.

Table 1
Properties Of The SMA Used

Properties	Value
Diameter in mm	0.305
Mass fraction of Ni in %	54.8
Mass fraction of Ti in %	45.2
Austenite start temperature in °C	82
Austenite finish temperature in °C	90
Martensite start temperature in °C	65
Martensite finish temperature in °C	55
Heat treatment	Straight annealed

The sheath materials for the development of SMA-HY are E-glass and polypropylene (PP) staple fiber rovings of 2000 tex and 4000 tex, respectively. The PP staple fiber rovings were used as sheath material to realize a more compact and dense fiber sheath. The diameters of glass and PP fibers were 17.12 mm and 47.62 mm, respectively.

As resin and hardener for the infusion of the functionalized preform, MGS® RIMR 135 and MGS® RIMH 137 (Hexion a. s., Sokolov, Czech Republic) were employed. They were mixed at a ratio of 10:3 by weight prior to infusion.

The most important properties of glass fiber rovings used for the production of functionalized preforms are listed in Table 2, which were determined by authors. The stress-strain behavior of the glass rovings was measured following the norm ISO 3341 on the tensile testing device Zwick Z 100 (Zwick GmbH & Co. KG, Germany). The test speed was set to 200 mm/min and the initial load was kept at 0.5 cN/tex. The test length was set to 500 mm. 15 measurements were executed in order to determine the average value and standard deviation.

Table 2
Properties Of The Glass Fiber Rovings Used For The Production Of Functionalized Preforms

Properties	Value	Standard deviation
Fineness in tex	1201	2.46
Breaking strength in N	540	34.1
Elongation at break in %	1.96	0.08

B. Production of SMA-hybrid yarn (SMA-HY)

In order to protect the matrix from direct contact with SMA, to ensure free and even mobility of SMA in FRP, and to fully exploit the deformation capability of SMA and therefore the adaption potential of the entire FRP structure, the wire-shaped SMA was converted into textile-based actuators in a core-sheath structure based on the friction spinning technology - DREF 2000. The spinning head of the DREF 2000 friction spinning machine for the production of SMA-HY is shown in Fig. 2. During this process, SMA is wrapped with glass and PP fibers to form SMA-HY. However, SMA were form-fitted to the reinforced fabrics to ensure force transmission from SMA to FRP. Production details of SMA-HY can be found in ref. [11].

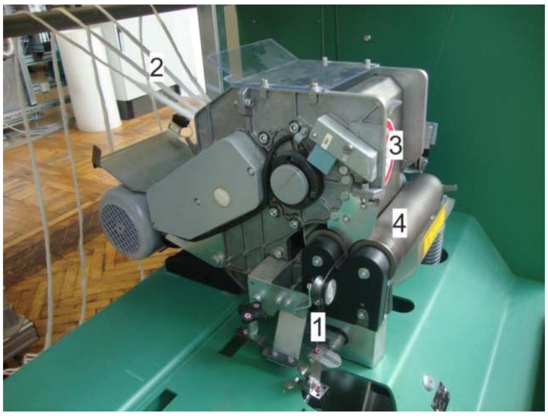

Fig. 2. Spinning head of the DREF 2000 friction spinning machine for the production of friction-spun SMA-HY (1: core feeding, 2: sheath feeding, 3: opening roller, 4: spinning drum) [11].

The microscopic view of produced SMA-HY is shown in Fig. 3.

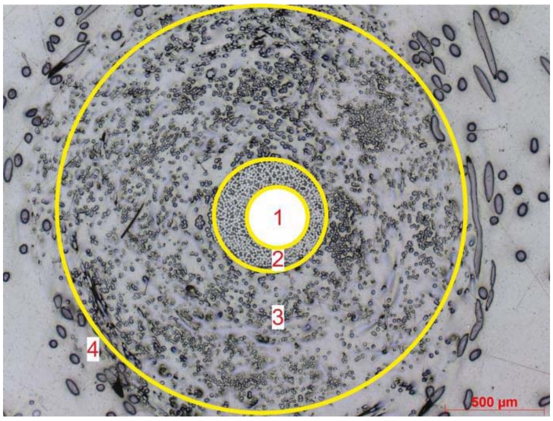

Fig. 3. Microscopic view of SMA-HY (1: SMA, 2: glass filament rovings, 3: glass staple fiber rovings, 4: PP staple fiber rovings).

C. Production Functionalized preform

The functionalized preform was generated on a rapier weaving machine type P1 (Lindauer Dornier GmbH, Germany). A hinged structure was developed during weaving for the realization of structure-integrated joint in adaptive FRP. The warp and weft yarn densities of the hinged and non-hinged areas are shown in Table 3.

TABLE 3
YARN DENSITIES FOR THE DEVELOPMENT OF A FUNCTIONALIZED PREFORM

Yarn density in yarn/cm	Hinged area	Non-hinged area
Warp	4	8
Weft	2.4	4.8

The hinged area was realized by plain weaving with floating warp yarns, whereas the non-hinged area was achieved with a multi-layered fabric including 3 sets of weft yarns. The floating warp yarns were cut after the weaving process. The functionalized preform during the weaving process is shown in Fig. 4.

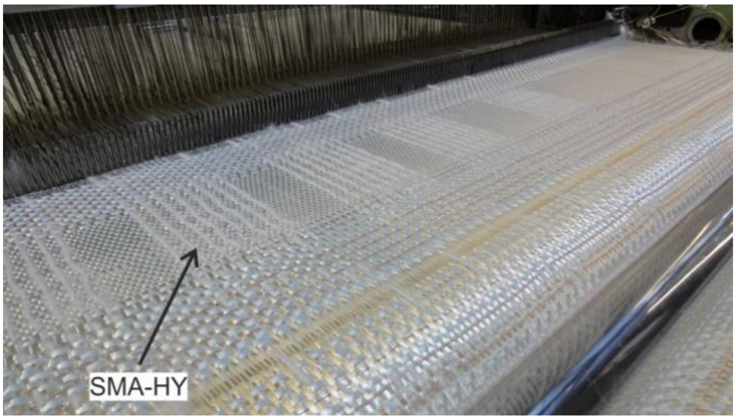

Fig. 4. Functionalized preform.

Prior to the infusion process, two types of functionalized preforms were prepared based on fully and partially sheathed SMA in lengths of 240 mm and 120 mm, respectively. By stripping the both sided sheath of SMA in non-hinged area, the partially sheathed SMA was realized. The reason behind this variation was to investigate the deformation behavior of adaptive FRP with variable sheath length of SMA. The electrical contating of two adjacent SMA was executed by means of welding in a meandering pattern.

D. *Infusion*

The adaptive preforms were infiltrated by the Seemann Corporation Resin Infusion Molding Process (SCRIMP), being a variation of the VARI process (Vacuum Assisted Resin Infusion). The decisive advantage of this method is the additional flow aid, which ensures the proper distribution of resin within the reinforcement structure. After infusion, the system was cured at room temperature for 24 h. Subsequently, the system was annealed at 50 °C for 15 h in a laboratory oven, so that the maximum degree of cross-linking of epoxy resin was achieved. Annealing at higher temperatures generally leads to reduced tempering times. However, in this particular case, this option was inapplicable since the SME of the SMA wire starts at approx. 80 °C. Adaptive FRP with fully and partially sheathed SMA after the infusion process are shown in Fig. 5. The hinged width and surface area of infused sample were 100 mm and 240*40 mm^2, respectively.

Fig. 5. Adaptive FRP with fully (top) and partially (bottom) sheathed SMA after the infusion process.

E. *Electromechanical characterization*

The SMA in the adaptive FRP was activated electrothermally by a laboratory power supply unit in addition to a current flow controlling unit. On- and off-times of the power supply were set to 60 s and 90 s, respectively. During on-time, the applied current flow was 1.9 A. No current flows were applied during off-time, causing passive cooling of the adaptive FRP. During the periodic heating and cooling cycles, the resulting deformation of the adaptive FRP was measured simultaneously by means of a laser triangulator. The test setup for the deformation behavior characterization of adaptive FRP is shown in Fig. 6.

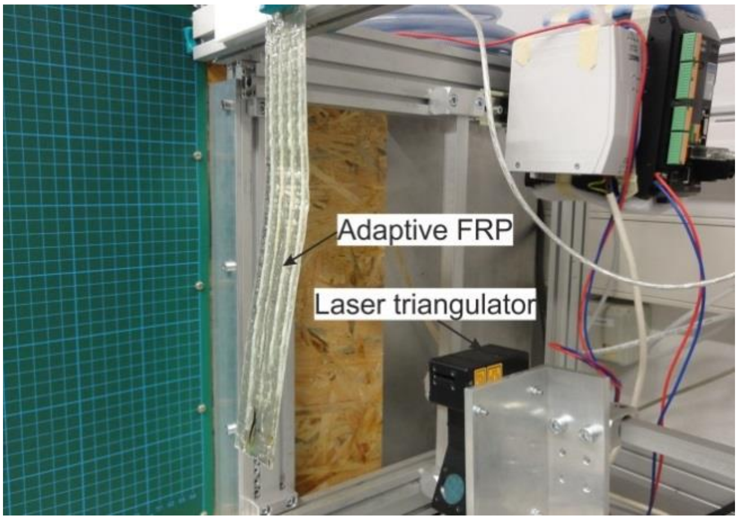

Fig. 6. Test setup for the deformation characterization of the adaptive FRP.

III. RESULTS AND DISCUSSION

The deformation behavior of adaptive FRP varies depending on the sheath length of SMA. Fig. 7 reveals that, by increasing the sheath length of SMA in adaptive FRP, the deformation of adaptive FRP is increased. This phenomenon can be attributed to the distance of the force transmission point from the hinged area. By increasing the sheath length of SMA, the force during the thermal induced activation of SMA is primarily applied on the area of the electrical contact.

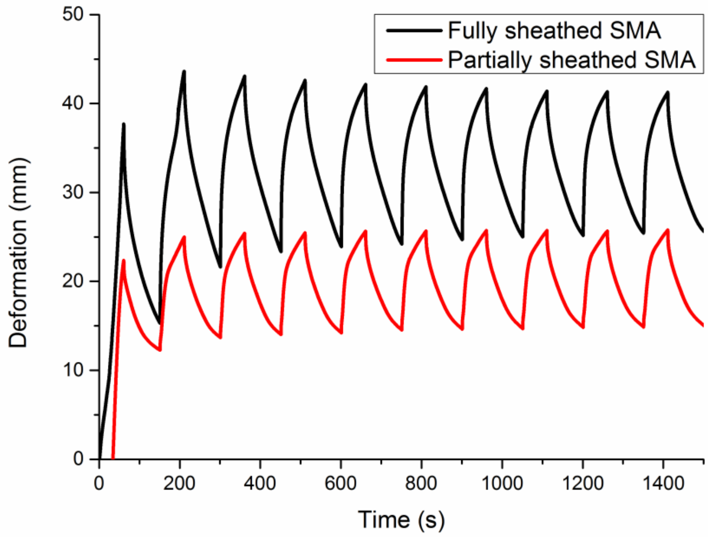

Fig. 7. Deformation curves of both types of adaptive FRP.

The deformation of both types of adaptive FRP is illustrated by a bar diagram (see Fig. 8). This bar diagram is based on the deformation curves of Fig. 7. The deformation of adaptive FRP is taken from the fifth heating and cooling cycle because from this cycle the deformation curves are relatively homogeneous over the remaining testing periods. It can be concluded from Fig. 8 that, by reducing the sheath length of SMA from 240 mm to 120 mm, the maximum deformation of adaptive FRP is reduced from 17 mm to 11 mm.

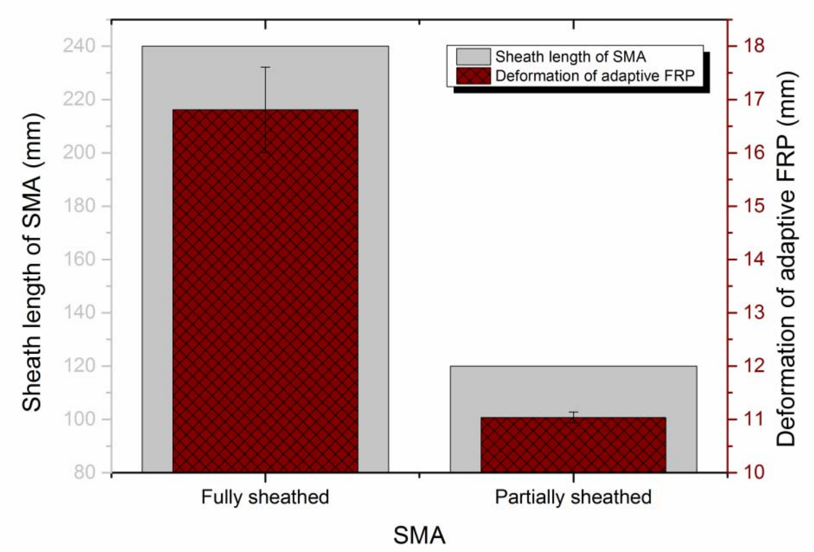

Fig. 8. Bar diagram for the deformation of adaptive FRP depending on sheath length of SMA.

IV. Conclusion

The development, realization and characterization of adaptive FRP were carried out within the research project presented in this paper. For optimum use of SMA in adaptive FRP, it was converted into core-sheath hybrid yarn. Subsequently, adaptive FRP were characterized by fully and partially sheathed SMA in lengths of 240 mm and 120 mm, respectively. After the thermally induced activation of SMA in adaptive FRP, it can be concluded that more deformation of adaptive FRP is achieved by increasing the sheath length of SMA.

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References

[1] C. Cherif. Textile Materials for Lightweight Constructions. Berlin, Heidelberg: Springer-Verlag GmbH, 2016. pp.1-35.
[2] M. Ashir, L. Hahn , A. Kluge, A. Nocke and C. Cherif, "Development of innovative adaptive 3D Fiber Reinforced Plastics based on Shape Memory Alloys", Composites Science and Technology 126 pp 43-51, 2016.
[3] M. Ashir, A. Nocke, C. Theiss and C. Cherif, "Development of adaptive hinged fiber reinforced plastics based on shape memory alloys", Composite Structures 170 pp 243-24, 2017.
[4] M. Ashir, J. Hindahl, A. Nocke and C. Cherif, "Development of adaptive pleated fiber reinforced plastic composites", Composites Science and Technology 148 pp 27-34, 2017.
[5] A. Kluge, A. Nocke, C. Paul, C. Cherif, T. Linse, V. Ulbricht, "Development and characterization of textile-processable actuators based on shape-memory alloys for adaptive fiber-reinforced plastics", Textile Research Journal 83(18), pp 1936–1948, 2013.
[6] M. Ashir, A. Nocke and C. Cherif, "Development and mechanical properties of adaptive fiber-reinforced plastics", Journal of Industrial Textiles, Epub ahead of print, DOI: 10.1177/1528083718757523.
[7] M. Ashir, J. Hindahl, A. Nocke, C. Sennewald and C. Cherif, "Development of adaptive pleated woven fabrics with shape memory alloys", Textile Research Journal, Epub ahead of print, DOI: 10.1177/0040517518792736.
[8] M. Ashir, D.M.P. Vo, A. Nocke and C. Cherif, "Adaptive fiber-reinforced plastics based on open reed weaving functionalization", Materials Science and Engineering 406 012063, doi:10.1088/1757-899X/406/1/012063, 2018.
[9] M. Ashir, J. Hindahl, A. Nocke and C. Cherif, "A statistical approach for the fabrication of adaptive pleated fiber reinforced plastics", Composite Structures 207, pp 537-545, 2019.
[10] M. Ashir, L. Hahn , A. Kluge, A. Nocke and C. Cherif, "Electro-bending characterization of adaptive 3D fiber reinforced plastics based on shape memory alloys", Smart Materials and Structures, 25 pp 035-041, 2016.
[11] M. Ashir, A. Nocke and C. Cherif, "Development of shape memory alloys hybrid yarns for adaptive fiber-reinforced plastics", Textile Research Journal, Epub ahead of print, DOI: 10.1177/0040517518770678.