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Sensing and Actuating Functions by Shape Memory Alloy Wires Integrated into Fiber Reinforced Plastics

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Abstract

Lightweight design based on fiber reinforced plastics (FRP) has potential for improvement by integration of sensors and actuators made of smart material filaments. Regarding FRP with integrated actuating shape memory alloy (SMA) wires, this paper presents important characteristics of such an adaptive composite and its components for design purposes. Beyond that, the first successful pultrusion processing of sensing SMA wires is proposed to address lightweight design mass production for safety-related applications. Measurements of this smart composite structure with strain sensor functionality proved high sensitivity compared to conventional sensors.

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Keywords: shape memory alloy wires; SMA; fiber refinorced plastics; FRP; lightweight design; smart composite structure; pultrusion

1. Introduction

Smart materials respond to changing environmental conditions in a suitable way for a certain application. This smart behavior requires a sensing as well as an actuating functionality [1]. This paper addresses the self-sensing and the actuating functionality of shape memory alloy (SMA) wires in separate ways. The first part focusses on SMA wires which are embedded as actuators in FRP to realize shape changing composites. In addition to this technology, the second part is focused on SMA wires with inherent strain sensor effect. Both examples demonstrate the great potential to improve lightweight design with structural integrated functions.

2. Material

Even though both examples are presented from a different point of view, the adaptive and the sensing composite are both made from glass fiber reinforced thermoset plastic with integrated Nickel-Titanium (NiTi) alloy (Table 1) and the respective findings are applicable for both differing manufacturing processes. The basic properties of the applied SMA wires are listed in Table 1. The phase transformation temperatures (A_s, A_f, M_s, M_f) of the NiTi actuator wire are above and those of the NiTi sensor wire are below the assumed ambient temperature of 20 °C in initial unloaded state. The phase transformation temperatures are critical material properties. They need to fit to the purposed application and to the surrounding polymer matrix to prevent accidentally actuation and heat damage.

Table 1. Properties of the applied SMA wires.

	NiTi sensor	NiTi actuator
Mass fraction of Ni in %	55.9	54.8
Austenite start temperature A_s in °C	-30	73
Austenite finish temperature A_f in °C	10	88
Martensite start temperature M_s in °C	-83	37
Martensite finish temperature M_f in °C	-120	24
Diameter in mm	0.150	0.500
Heat treatment	straight annealed	straight annealed

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Surface condition	oxidic	oxidic

3. Adaptive composite

Thermal SMA wires perform as actuators with high energy density when twinned martensite phase is present at low temperature [2]. Shape changing lightweight composite structures are feasible by integrating NiTi actuator wires. For this purpose, vacuum infusion manufactured glass fiber reinforced epoxy resin is herein applied. The resulting composite structure is assumed to be thermally activated by ambient temperature to adapt to environmental conditions. Alternatively, the activation could be performed through resistance heating of the SMA wire by an electric power supply. An exemplary application for ventilation purposes or temperature control is shown in Fig. 1.

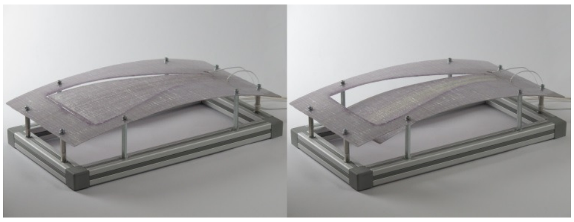

Fig. 1. Adaptive ventilation flap made of FRP and integrated SMA actuators.

The working principle of such an adaptive composite structure is based on the reversible mechanical interaction between the structural FRP stiffness and the uniaxial SMA wire forces [3]. A SMA volume fraction of at least 1 % is necessary to deform a glass fiber reinforced plastic. The adaptive ventilation flap (Fig. 1) has a thickness of 2 mm and a width of 30 mm. Four NiTi actuator wires with a diameter of 0,5 mm are capable to induce a significant bending deformation. Since the SMA wires are thermally activated, such an adaptive composite needs to be designed considering both heat transfer and force transmission. The bending deformation is a consequence of the heat induced tension by the off-center integrated actuator wires. According to [4], the anisotropic and temperature dependent viscoelastic behavior of composite structures can be simplified to anisotropic linear-elastic behavior for short-term loads and low humidity environments. This simplification can be applied to glass fiber reinforced and temperature-resistant epoxy resin, which are used here. Besides the direction-dependent mechanical behavior of the FRP, the temperature-dependent stress-strain curve of the NiTi actuator wire is necessary to describe the adaptive composite behavior. The force transmission between the wires and the polymer matrix is not achievable by the interface shear strength and has to be assured by additional tight fit [5]. The mechanical interaction is also influenced by the different thermal expansion coefficients of the components [6,7]. Another aspect is the load dependency of the SMA phase transformation temperatures. Those values increase approx. 10 K per 85 MPa stress increment [8]. On the one hand, in case of direct resistance heating of integrated NiTi actuator wires, the thermal conductivity of FRP depends on temperature and fiber volume fraction but not on the layup. On the other hand, the heat loss is driven by convection and thermal radiation of the hole composite. Regarding the wire surface condition there is not recognized any effect on the interface heat resistance between wire and FRP. [9]

The specific heat capacity of the composite components, the glass transition temperature of the polymer and the phase transformation enthalpy of SMA wire can be determined by differential scanning calorimetry. Those values are essential to determine the amount of thermal energy required to activate the adaptive composite and to avoid overheating damages of the FRP and SMA.

4. Sensing composite

SMA wires are also capable to work as strain sensors. Along with the stress-induced phase transformation (from austenite to detwinned martensite and vice versa under constant temperature), the ohmic resistance undergoes a large variation [10]. Consequently, the bijective correlation between changes in electric resistance and changes in mechanical strain of the NiTi sensor wire qualifies this material for the implementation in strain gages.

The electrical resistance of metallic sensor wires is determined by geometry and structural change (also known as piezoresistive effects) [11]. According to [12] the temperature influence can be compensated and thus will be neglected here. The wire geometry (diameter and length) changes when an axial load is applied. Poisson's ratio ν represents the changing diameter in relation to changes in length. Conventional strain gauges apply this geometrical effect as measurement principle (term one in equation 1). Piezoresistive effects (term two in equation 1) are usually negligible for most metals [13].

$$\frac{\Delta R}{R} = \left[(1+2\cdot\nu)\frac{\Delta L}{L}\right]_1 + \left[\frac{\Delta\rho}{\rho}\right]_2 \quad (1)$$

The strain measurement sensitivity can be expressed by the gauge factor k (equation 2). If the piezoresistive effects are also negligible for NiTi sensors, the expected k-factor would be between 1.6 and 1.9 for typical Poisson's ratios of NiTi given in literature ($0.3 < \nu < 0.45$ [14]).

$$\frac{\Delta R}{R} = k\,\frac{\Delta L}{L} \quad (2)$$

Strain dependent electrical resistance measurements of the NiTi sensor wire were carried out with the commercial digital multimeter Agilent 34401A and the material testing machine Zwick Z020. A nearly straight proportional behavior and the typical temperature dependent stress-strain-hysteresis of NiTi is recognizable (Fig. 2). The temperature influence on the