DOI 10.5162/sensor2017/D4.1

Shape memory strain gauges

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Abstract

Reinforced and plain polymers are highly elastic. In order to measure strain of parts made of these, strain sensors have to be highly elastic too. Such sensors, certainly for cyclic loading conditions with high amplitudes, are not available.

Pseudoelastic shape memory alloys are used to realise high performance strain sensors with high elasticity. These sensors can be elastically strained up to 80,000 µm/m. In cyclic loading conditions strain levels or amplitudes of about 20,000 µm/m are possible. The high elasticity stems from the stress-induced phase transformation of the SMA. This phase transformation involves a comparably strong specific electrical resistivity change together with long elastic strain variations. The determined gauge factor exceeds 5 and is higher than that of most of the conventional metallic strain gauges. Sensor structures can be made of wires. These can be embedded into plastics and fibre reinforced plastics. The integration of sensors is possible via injection moulding, laminating and infiltrating processes.

The paper presents recent results of the development of shape memory alloy strain gauges.

Key words: Shape Memory Effect, Shape Memory Alloy, Pseudoelasticity, Strain Measurement, Strain Gauges

Introduction

Electrical strain gauges can be used for load monitoring of metals based construction materials. Their fatigue strength is higher compared to the metals. Thus these strain gauges do not break before the metal in fatigue tests or under cyclic loading conditions. Composite materials have a higher fatigue strength compared to conventional metal based construction materials (Fig. 1).

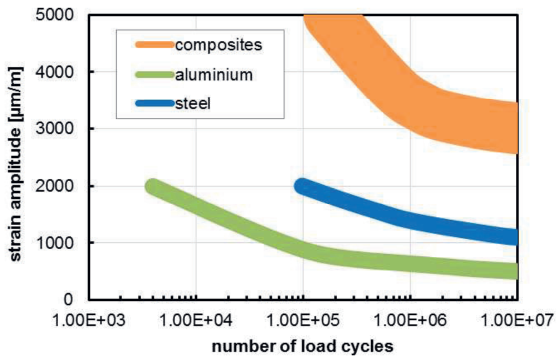

Fig. 1 Fatigue behaviour of different construction materials [1].

Conventional electrical strain gauges would break before the composite under cyclic loading. They are therefore not eligible for monitoring application on composites.

There are some alternative sensor and measurement technologies for testing and infrastructure applications. Digital image correlation and laser speckle extensometer can be used as non-contact techniques to monitor strain. But this technique can only be applied in laboratory conditions. Fibre Bragg grating (FBG) sensors can be used as a contact method to monitor strain. But the electronic measuring equipment for these optical sensors is complex, expensive and voluminous. Therefore it is not suitable for mobile applications. Carbon fibres can also be used as strain sensors in composites. Their gauge factor is comparably low and measurements are highly temperature dependent. All these alternative methods and techniques still face a lot of challenges or comprise enormous disadvantages. An alternative strain sensor with high elasticity, high fatigue strength and simple monitoring equipment is therefore needed.

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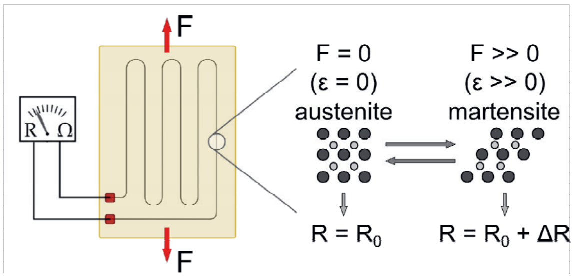

Fig. 2 Working principle of SMA strain gauges.

Pseudoelastic shape memory alloys (SMAs) are used in medical applications, mainly in the form of stents to keep anatomic vessels open. The term pseudoelastic reveals that the SMA shows an elastic behaviour with strain levels of up to 80,000 µm/m when it is deformed at room temperature. The enormous elastic strain level is possible due to a reversible stress-induced phase transformation of the material structure. An electrical application of this effect is described in [2]. The wire is used as flexible electrical conductor. Since copper wires have a limited elastic limit, they tend to strain-harden when deformed and break due to fatigue. SMA could overcome this drawback. It is also possible to shape the SMA wire using thermal treatments. Without stress, the pseudoelastic SMA always tends to regain this initial shape. A SMA wire could fulfil a self-rolling function using this effect [2].

The solid-solid phase transformation is also combined with a significant change of the electrical resistance [3]. The resistivity variation can be used as a sensing signal [4]. It is therefore possible to use SMA as a strain monitoring sensor (Fig. 2). SMA sensors can be attached or integrated for fiber-reinforced plastics (FRPs) monitoring applications [5].

The resistivity change of SMA is already used to determine and control the position of SMA actuators. It is possible to stably hold positions and to drive the actuator accurately by means of the resistivity signal. Additional strain sensors were unnecessary [6].

The application of SMA as strain sensor for polymer parts is described in a patent of van Schoor et. al [7]. In addition to attaching and embedding, the weaving and stitching integration into textiles is possible. The combination of SMA sensors with FRP is not shown there. Processes or technologies for the manufacture of certain sensor structures are not specified. The temperature dependence and methods for the temperature compensation are not mentioned as well. Another patent describes the embroidering of SMA for FRP integration [8]. The applied type of SMA is not specified in this document. The disadvantage of embroidering is that plastic deformations of the SMA could be introduced in this process. This can negatively affect the sensor effect.

Experimental and materials

In order to investigate the sensing properties as well as the mechanical properties of the plain SMA, the wires itself were tested at first. A pseudoelastic SMA wire with almost stoichiometric NiTi composition and a diameter of 50 µm was used for the investigations. The wires were characterized in the as-received (straight-annealed by the producer) and in a heat-treated state. Heat treatment is necessary to shape the wire into sensor structures, e. g., into meander-like structures. Tensile tests, using a Zwick material testing machine, in combination with electrical resistivity measurements, by means of an Elabo resistivity meter, were carried out to achieve mechanical and electrical data of the wires. The wires were therefore cut into segments with a length of 300 mm. Subsequently, a crimp sleeve was fixed on each end of these wire segments. The wires were then fixed in a ceramic lustre terminal, which was fixed in the standard clamp of the testing machine. The lustre terminal was needed in order to guarantee the electrical isolation of the wires to the testing machine in combination with a reliable mechanical fixation of the wires. The measurement data of the Elabo device were directly captured by the software of the testing machine via an analogue interface. The synchronicity of the electrical data with the mechanical data is thereby guaranteed. The electrical resistivity change ΔR was calculated out of the actual resistivity R and resistivity R_0 at start according to equation (1) and the gauge factor k using equation (2).

$$\Delta R = \frac{R - R_0}{R_0} \cdot 100\% \quad (1)$$

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

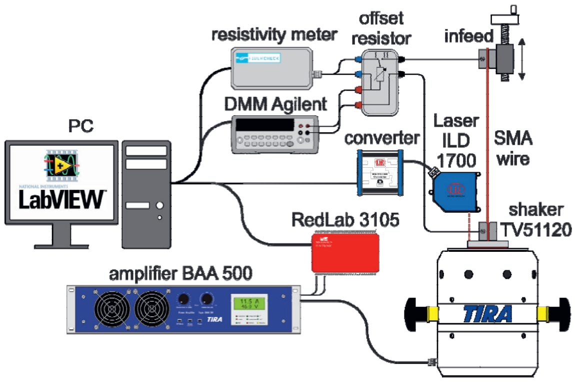

Fig. 3 Fatigue testing setup for cycling of SMA wires and monitoring the electrical resistivity.

For the sake of getting a first impression of the long-life behaviour of the SMA sensor material, fatigue tests were carried out. A particular testing machine was built to cycle and monitor the wires (Fig. 3). Straight wires with a length of 200 mm were tested. The strain movement was induced by an electro-dynamic shaker. The movement was controlled by a specific LabView program using a laser extensometer as actual position input signal. An oscillation frequency of 2 Hz was used so far. Simultaneously to the movement the electrical resistivity of the SMA wires was monitored with a distinct resistivity meter with a high sampling rate. The fixation of the wires in the fatigue tests was realised by means of flat clamping jaws. A bezel with a radius of 2 mm was generated on the inner edge of the clamps in order to minimize or omit the notch effect in contact between the SMA wire and the clamps. Wire breaking at the clamps was observed in the first tests. An optimization solved this problem successfully.

Another important parameter of strain sensors is the temperature dependence of the sensor signal. It is necessary to differentiate between the signal change caused by strain and by temperature change. When the temperature sensitivity is known, the signal change due to temperature can be compensated. For this reason the resistivity tolerance over the temperature range was determined. It was carried out using a climate chamber, resistivity and temperature measurement equipment (Keithley 2000 DMM and Meilhaus RedLab TEMP AI with type K thermocouples respectively). The resistivity was measured by means of the four-wire method. The SMA wire specimens were crimped using end sleeves and then contacted on them. The measured variables were simultaneously recorded by a proprietary LabView program communicating with both devices. The temperature range was between -40 °C and 100 °C.

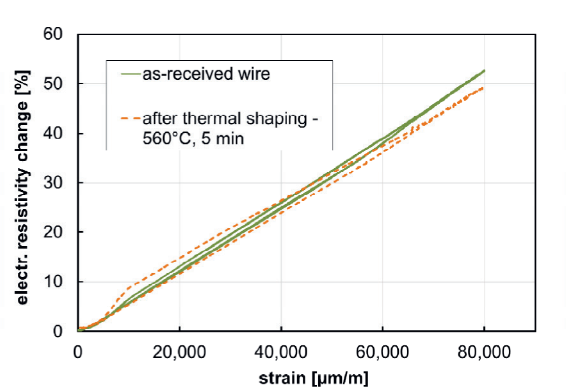

Fig. 4 Representative curves of the electrical resistivity change of strained pseudoelastic SMA wire for the as-received state and after thermal heat treatment.

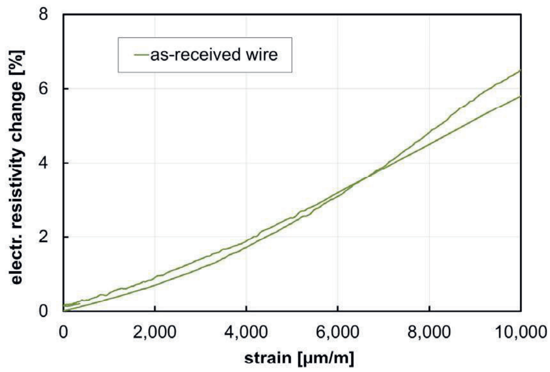

Fig. 5 Magnification of a representative curve of the electrical resistivity change of strained pseudoelastic SMA wire for the as-received state.

Results and discussion

The electrical resistivity change of pseudoelastic SMA wire in the as-received state is nearly linear for strain levels up to 80,000 µm/m (Fig. 4). For small strain levels below 10,000 µm/m the resistivity change is exponential (Fig. 5). Since Fig. 5 displays only a section of the whole strain range, the hysteresis would be smaller compared to a maximum deformation of 10,000 µm/m.

The as-received wire displays a slight hysteresis of the resistivity signal. This hysteresis increases with thermal heat treatment (Fig. 4). This hysteresis is related to the formation of rhombohedral phase (R-phase) [3]. R-phase has a higher resistivity in comparison to martensite. This is the reason for a steeper slope of the resistivity change at small strain around 10,000 µm/m. Due to the heat treatment the formation of R-phase is strengthened. This is because the residual stress state and the microstructure of the SMA are modified by the heat treatment so that formation of R-phase is promoted. That is why the heat treatment should be delimited to a minimum.

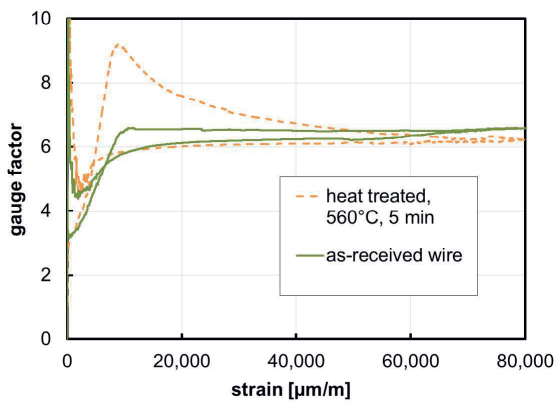

Fig. 6 Diagram of the gauge factor tolerance over the full strain range from 0 to 80,000 µm/m of pseudoelastic SMA wire.

DOI 10.5162/sensor2017/D4.1

The tolerance of the gauge factor over strain clarifies this behaviour (Fig. 6). Below 10,000 µm/m the gauge factor of as-received wire constantly raises from about 3.2 to 6.6. After this the gauge factor is almost constant – only slightly decreasing (6.6 to 6.5). With unloading a reduction of the gauge factor can be seen from 6.5 to 6.3. It is then constant down to 20,000 µm/m. Another decrease can be found with complete relief. This reduction is low over 10,000 µm/m. Out of these results it can be deduced, that the pseudoelastic SMA in the as-received state shows the best sensor properties at strain rates higher than 10,000 µm/m. The gauge factor is almost constant and only slightly different in comparison between loading and unloading. For small strain changes this difference is expected to be even smaller.

For the heat treated SMA wire the tolerance of the gauge factor is extremely higher (Fig. 6). The influence of the formation of R-phase leads to a peak gauge factor of about 9 around 10,000 µm/m. The change of the gauge factor is enormous before and after that peak. The unloading profile is comparable to the curve of the as-received wire. This result emphasizes the above mentioned conclusion about the delimitation of the heat treatment. The heat treatment strongly affects the sensor function.

The fatigue properties of pseudoelastic SMA wire are, as far as they could be tested, considerably advantageous compared to conventional strain gauges (Fig. 7). In a running fatigue test with a strain maximum of 5,000 µm/m more than 1,000,000 cycles were reached. The results of the first tests with higher strain rates still comprise to low cycle numbers due to breaking at the fixation.

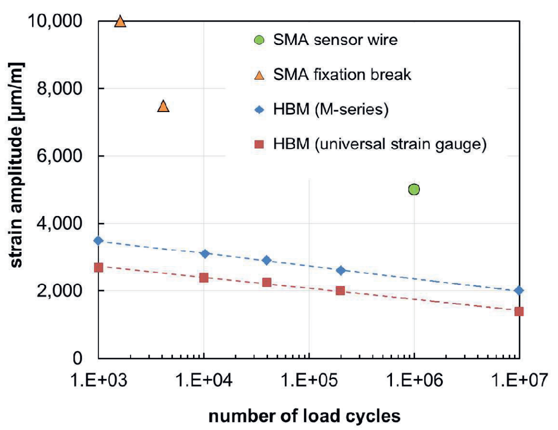

Fig. 7 Fatigue behaviour of pseudoelastic SMA wire compared to conventional strain gauges – SMA wire broke at the fixation in first 2 points (triangle), last point (circle) is actual value of a running fatigue test with optimized clamping jaws.

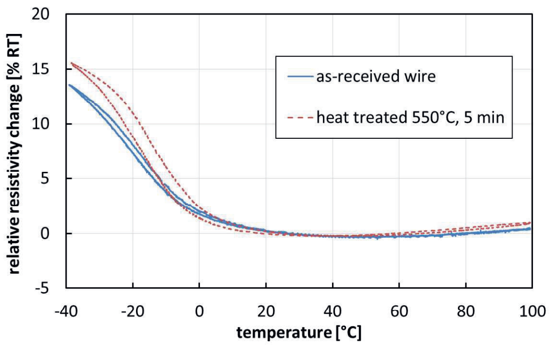

Fig. 8 Diagram of the resistivity tolerance over the temperature range for a: as-received and heat treated pseudoelastic SMA wire.

The cyclic loading tests have to be repeated in order to display the full functionality of SMA according to fatigue. Higher values are certainly expected.

The curves of the resistivity tolerance over the temperature have a common trend. In the temperature range between 20 °C and 100 °C the resistivity change is small in a range of ±1 % (Fig. 8). Below this temperature range the resistivity strongly increases. The reason of this increase is the thermally induced formation of R-phase. Additional DSC measurements proof this cause. The magnitude and starting temperature of the R-phase transformation depends on the treatment of the wire, as mentioned before. The thermal treatment of the SMA wire increases the magnitude of R-phase formation. Out of these results it can deduced, that a compensation method is needed for low temperature applications.

Summary and conclusion

Pseudoelastic SMA wires were successfully characterized in order to evaluate their strain sensing capability. Mechanical-electrical, dynamical and thermal-electrical properties were determined to evaluate the sensing value of this material. The results reveal that pseudoelastic SMA is suitable for strain sensing. It is elastic in a broad range and shows a gauge factor higher than 5. The fatigue behaviour is far better compared to conventional strain gauges. This is advantageous certainly for applications in structural health monitoring of FRP and for fatigue testing of composite or plastic parts. The temperature range is actually limited or sensors need temperature compensation.

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