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Functional and Economical Evaluation of Reused SMA Actuators

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Abstract: Shape memory alloys are characterized, among others, by high workload, noiselessness and electromagnetic compatibility. Their special thermal behavior offers a wide range of configuration options. In this context, one unique property is that SMAs (shape memory alloys) can recover their mechanical properties to a certain degree by heat treatment. This distinguishes them from most materials which are worn out when in use, which makes maintenance necessary. The purpose of this paper is to investigate the change of properties of reused SMA actuators. The traditional maintenance processes for SMA actuators and maintenance processes based on reused SMA actuators are presented and discussed. Additionally, experiments are performed in order to evaluate the re-use SMA actuators. The SMA actuator is evaluated through key performance indicators. Finally, the paper evaluates the reuse of SMA actuators from a technical and economical perspective based on a requirement profile of a certain SMA actuator. The replaced reused SMA actuator system is compared to a replaced new SMA actuator system. Future studies should consider various parameters of the heat treatment and its effect on the key performance indicator of SMA actuators.

Key words: Shape memory alloys, heat treatment, actuator, material, self healing, fatigue.

1. Introduction

The product understanding is changing. Nowadays products must be, first of all, easy to use but also safe. In the field of mechanical engineering, this means that the manufacturing companies wish to exclusively concentrate on the production of goods, but do not want to care or are not able to care about maintenance and fault diagnosis of machinery. Companies want to use machines but decreasingly care about maintenance or fault diagnosis. Nevertheless, maintenance costs are significant [1]. This is why proper maintenance approaches are more and more important for the customer. In the field of small-to-medium-sized actuator applications, shape memory alloys based actuator systems (SMAS-ASs) are a promising technology. Besides their advantageous physical and mechanical properties, the thermal sensibility and regeneration has the potential for easy and resource-efficient maintenance processes. However, investigations about regeneration, usage and maintenance processes are still missing.

The paper is organized as follows: Section 2 gives an overview of SMAs and SMA-based actuator systems (SMA-ASs) including the usage, as well as basics about the regeneration of SMA-ASs. Section 3 describes the experimental design and set up. The results are discussed in terms of mechanical properties. Based on the findings, the next section highlights the possibilities for a reuse of SMA-ASs and evaluates them economically. Finally, Section 5 closes by summing up the key findings and thus by presenting how the paper makes a significant contribution within the research field.

2. Basics

2.1 Shape Memory Alloy Based Actuators Systems

SMAs (shape memory alloys) belong to the group of active materials with direct coupling for actuation [2]. SMAs are able to remember a previously trained shape after deformation. This ability can be used by thermal or mechanical activation. The application fields of

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SMAs are divided into the pseudoelastic effect and thermal effect.

The pseudoelastic effect is stress-induced and leads to a reversible deformation depending on the level of stress. This effect applies in most of today's shape memory applications, especially in the field of medical devices. The thermal effect is characterized by heating without load, the shape regains its former deformation. The area of particular interest exhibits the extrinsic two-way effect for actuator application because of its reproducible reversible deformation [3]. This effect is characterized by its ability to change the shape under cyclic thermal load without the use of mechanical load [2].

SMAs usually have a phase transformation with a hysteresis of up to 30 Kelvin. Depending on the alloy transformation temperatures, the temperature in use is between -100 and +100 °C [4, 5]. According to Ref. [2], NiTi-SMAs have the highest energy density of around 3000 Joule/kg of today's actuator principles. In addition to that, the effect in use varies from 4-8 percent stroke depending on the type of effect. Thus, NiTi-SMAs are corrosion-resistant and biocompatible with greatest effect and long-term stability [5, 6]. Additionally, "self-sensing" can be used as sensors and control purposes [5, 7].

In industrial applications, actuators and SMA-based actuators are mainly used as main components of mechatronic systems. Mechatronic systems consist of a mechanical structure, actuators, sensors and a unit for processing information [8-10] as well as periphery components. In the simplest case, SMA-ASs are composed only of an SMA-actuator, the mechanical structure and periphery, like in Refs. [11, 12]. If control is needed, a micro controller is added [13]. SMA-based actuators can be used as an actuator and sensor at the same time depending on the relevant state variable [14]. Fig. 1 illustrates the basic structure of an SMA-wire actuator system.

In today's industrial applications, SMAs are interesting for a wide range, especially valves [12], locking and unlocking mechanisms [7] or vibration damping applications [2, 15]. A broad range of applications for shape memory actuators are discussed in [2, 15, 16].

Nevertheless, significant obstacles for the use of SMAs in industrial applications are often higher prices compared to conventional solutions like electric motors [17], a limited temperature range of phase transformation and difficulties in processing [17, 18] as well as actuator development.

2.2 Lifecycle of Shape Memory Alloy Based Actuators

Fig. 2 illustrates the physical lifecycle of SMA-AS with the focus on wire actuators. The industrial processing of SMA-wire actuators consists of four basic steps: melting, hot and cold working, wire drawing and the training [16].

Heat treatment or training influences SMA-properties like cyclic stability, realizable displacement and the phase transformation temperature [19]. Within a cutting process, the length of an SMA wire actuator can be defined. The connection technology is rather complex. Welding is possible but

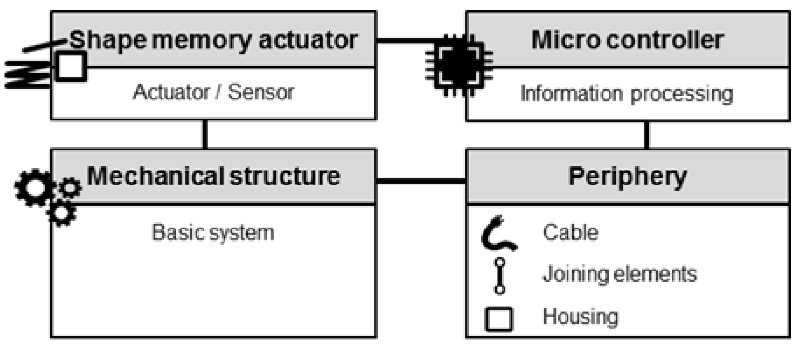


Fig. 1 Basic structure of an SMA-wire actuator system.

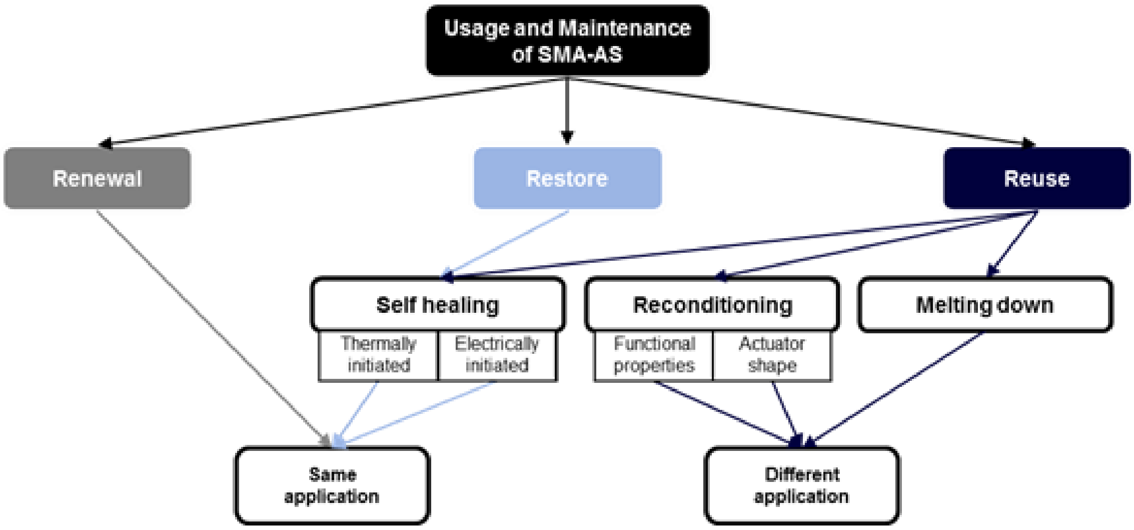


Fig. 2 Schematic overview of the lifetime of an SMA-wire actuator system.

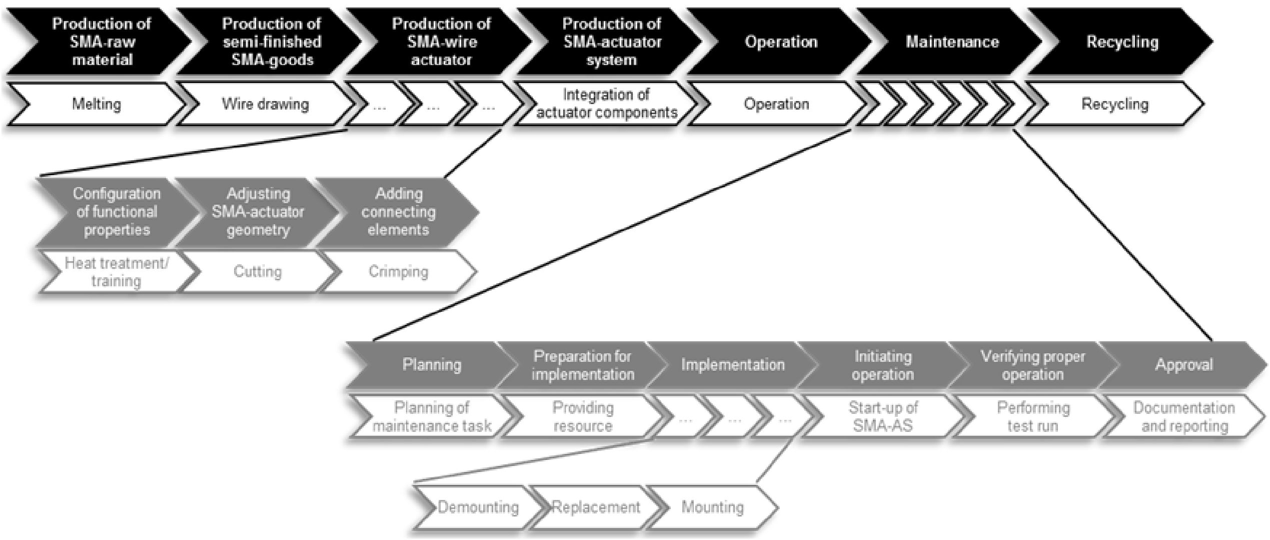


Fig. 3 Possibilities for (re-)using SMA-AS.

challenging due to the temperature sensitivity [20-22] suggests the use of crimping and force and locked connections. Crimping applications are small by size, simple, cost-efficiently assembled and able to fulfill industry standards [23].

SMA actuators wear out in use due to structural and functional fatigue [24], whereby maintenance is necessary. The steps for a maintenance process of a technical system are according to Ref. [25] and are schematically shown in Fig. 2. Regarding usage and maintenance, SMA wire actuators have special features, which are illustrated in Fig. 3.

If it is necessary to replace an SMA-AS, the first possibility is to renew the SMA-AS by a newly produced SMA-AS. It is also possible to extend the need for maintenance by using a redundant actuator design [26]. The most interesting possibility is to restore actuator properties through a SH (self-healing) or heat treatment. The adequate type of self-healing is chosen on the basis of the required effort. Furthermore, the resource efficiency can be increased by reusing SMA actuators for different applications. Changing the shape of SMA actuators, for example the size or the length, or using heat treatment to reconfigure the activation behavior can reduce the required resources for production. Moreover, by melting down SMA actuators, the material can be reused for actuator production.

2.3 Fatigue and Regeneration of Shape Memory Alloy Based Actuator Properties

According to Ref. [24], two types of fatigue can be distinguished. The first is structural fatigue caused by microstructural damage during cyclic loading, which leads to a loss of structural integrity. Structural fatigue is influenced by alloy subsystems, ambient conditions and thermo-mechanical pretreatments. The second is functional fatigue caused by working displacements or dissipated energy in cycling, which leads to changes in functional properties [27]. Functional fatigue is influenced by displacement, cycles, load and control. Both types are influenced by ambient system and connection methods [28]. Obviously, structural and functional fatigue have an impact on the maximum number of cycles to fracture and technical characteristics of SMA actuators.

Most products are worn out during use, which makes maintenance necessary. Unlike most materials, SMAs can recover their original mechanical properties by heat treatment. For this, the SMAs have to be exposed to a certain temperature for a defined time, which can be done through a controlled current or annealing process [28-30].

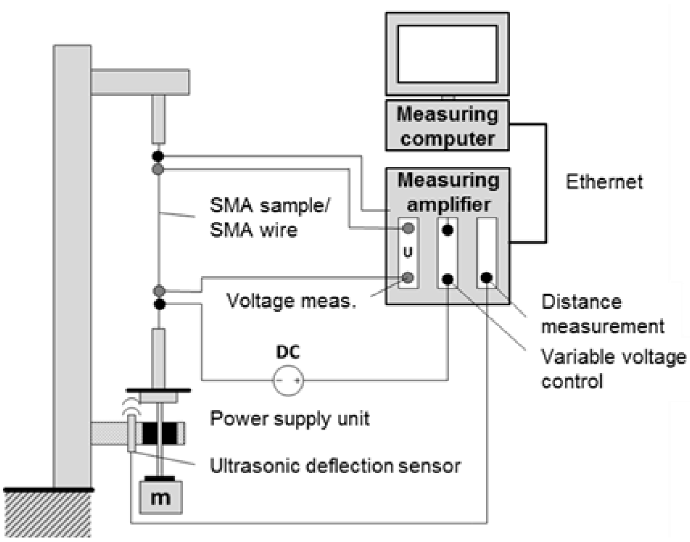
Langbein et al. [28] investigated thermal initiated self-healing for SMA-wire actuators after 100 cycles at a heat treatment temperature between 200 °C to 700 °C for 5 to 20 minutes. For the heat treatment procedure, the SMA wire actuator was decoupled from the loaded force. Best results were gained by temperatures around 250 °C. In this case, the previous displacement of 4.5% was restored completely. Nevertheless, Langbein et al. [28] examined only at low numbers of activation. Above 400 °C, no self-healing effect was observed.

Pilch et al. [31] investigated the healing of pseudo-elastic NiTi shape memory alloys for a higher number of cycles at a heat treatment temperature between 100 and 300 °C for 10 seconds up to 20 minutes. Their experiments indicate that self-healing works for both: functional and for structural fatigue. By periodic heat treatment it is possible to enhance the useful time of SMA actuators. The heat treatment has to be performed before permanent damage gets created [31].

3. Experiments Investigating Regeneration to Restore Properties of Shape Memory Alloy Based Actuators

3.1 Experimental Set Up

Fig. 4 shows the experimental set up which has been used to investigate the ability of shape memory alloy



List of detailed components of the experimental set up		
Component	Name	Producer
SMA-wire	Smartflex90°C	memry
Connecting elements	Crimpings	n/a
Power supply unit	EA-PS 3016-20B	EA
Ultrasonic deflection sensor	UNAM 18P1703	Baumer
Measuring amplifier	MGCPlus	HBM
Measuring software	CatmanEasy	HBM
Heating furnance	N 15/65HA	Nabertherm
Measuring computer	Latitude D620	Dell

Fig. 4 Experimental set up for regeneration of SMA-AS.

based actuators to restore their properties. The experimental rig is able to run five experiments simultaneously.

In total, 10 samples have been used to evaluate the regeneration of SMAs. The samples are made from SMA wires with an activation temperature of As 90 °C, a diameter of 0.15 mm and a length of 100 mm. The SMA samples are activated by a power supply unit. Constant current pulse is used because it is easy to set up and all cycles get the same activation. The activation time is set to 1 second, heating with a current of 0.6 A and the cooling time is set to 8 sec. Eyelets are crimped at the SMA wire ends, which is why it is necessary to fasten them in the experimental rig. The SMA wires are fastened in a mounting, loaded on a weight, and guided through an axial plain bearing and loaded at a constant force of 400 MPa. The power supply unit is connected with alligator clips to the SMA wire eyelets. A measuring amplifier records the measurements, which includes voltage, current, force and displacement.

The lifetime of the SMA sample is designed for about 10,000 cycles. In the experiments, the heat treatment is performed after 2,000 and 6,000 cycles. In addition, a reference experiment is made without heat treatment. The heat treatment temperature is 300 °C for 5 minutes.

3.2 Results

The average maximal displacement range of all test series is identical regardless of the heat treatment, whereby the plausibility is given. As seen in Fig. 5, heat treatment serves to completely restore the maximum displacement and functionality.

As long as functional fatigue is the reason for the replacement of actuators, this can be remedied by using self-healing. The experimental results demonstrate that it is possible to define limits for the actuator displacement of an SMA actuator at which heat treatment is necessary. The minimum limit determines the frequency of heat treatment and thus on the required effort to ensure the functionality of SMA-AS. For measuring the displacement, sensors are necessary. For this purpose, the “self-sensing” properties of SMA can be used [32]. Nevertheless, it has not been possible to confirm the assumption of Ref. [31] to extend the useful life of NiTi-SMA actuators with the experiments under the parameters considered. An explanation for this is, according to Ref. [31] structural damage prior to heat treatment which cannot be regenerated.

4. Possibilities for the Reuse of SMA-ASs and Economical Evaluation

4.1 Options for the (Re-)Use of Shape Memory Based Actuator by Regeneration

Based on the results in Chapter 3.2 and the usage of SMA-ASs presented in Chapter 2.2, options for using SMA-ASs in terms of required material and time are now presented. The linkage between processes and value chain and the potential for innovative products is

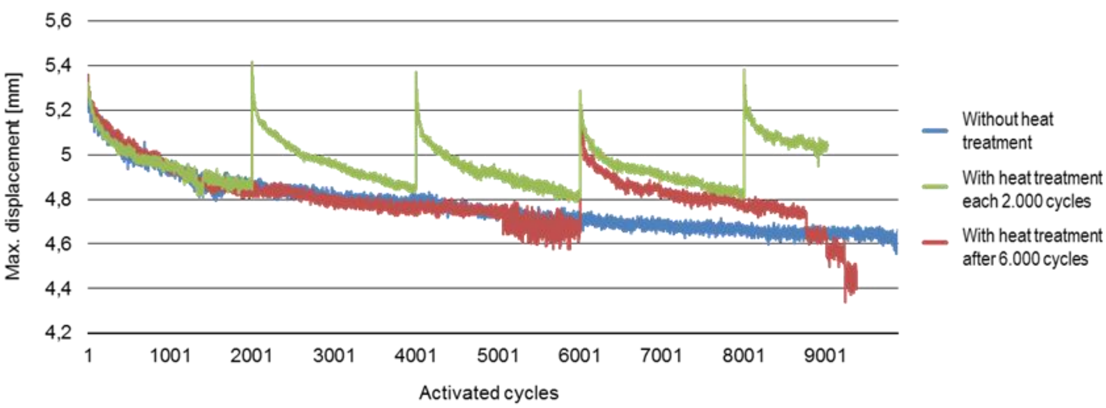


Fig. 5 Long-term experiments with and without heat treatment for SMA wire actuators.

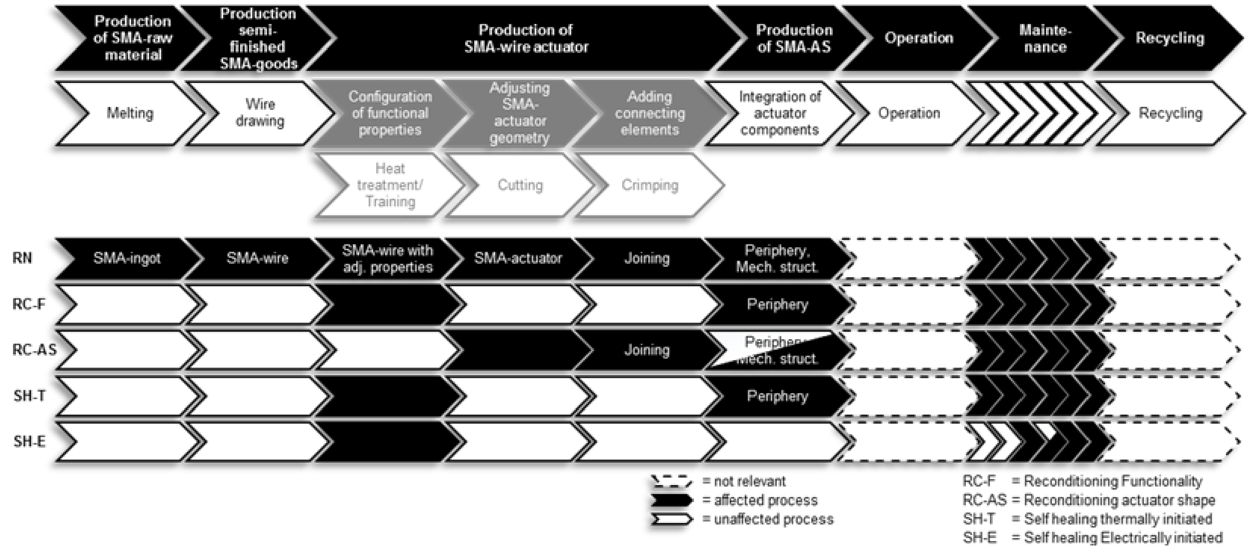


Fig. 6 Required resources and processes depending on the use of an SMA-wire actuator system and type of maintenance.

discussed in Ref. [33]. Fig. 6 illustrates the required resources for different approaches to use SMA-ASs. In the process steps, required materials are presented. Affected processes are highlighted in black.

The most resource-intensive case is the renewal of SMA-AS by producing a (complete) SMA-actuator system to replace the existing SMA-actuator system. In this case, the maintenance approach is traditional. Restoring functionality and expanding the period of use of existing actuators through self-healing is marked by the lowest use of resource. At best, it is possible by electrically initiated SH to repair an actuator system with very little time exposure. The process flow for maintenance of thermally initiated SH corresponds to a "renewal" but here the actuator, SMA-actuators or SMA-ASs are replaced by reused ones. As a result, the required material can be reduced. Pilch et al. [31] highlight a major advantage of SH, which lies in enhancing the fatigue life of SMA-actuators when dismantling whole structures to replace old, fatigue wires with new ones might be too expensive or simply just not possible. The reuse by RC (reconditioning) is particularly interesting for actuator classes with identical dimensions but different operating requirements like changed phase transformation temperatures or displacement through heat treatment, which is a reconditioning of the actuator functionality. For actuator series which have different mechanical requirements, especially regarding actuator performance (e.g. number of cycles, displacement, and force) RC by new shaping of SMA-actuators is an option. The degree of change between old and new SMA-AS determines the necessary process steps and required resources.

The sensor characteristics and self-healing of SMA actuators may allow for a condition-based maintenance for simple actuator systems [13]. With the properties of SMAs, new solutions in the field of smaller actuators are possible and thereby new business models can be introduced [26]. This includes, for example, service-oriented business models in more complex environments where collaborations are required [34]. In addition, SMA actuators are suitable for the partial automation of recycling processes due to their thermal behavior [35, 36].

4.2 Profitability Analysis of the Regeneration of Shape Memory Based Actuators

For the use of a technical solution in industrial environments, the costs of a solution, in addition to technical requirements, are critical. For this reason, it is essential to analyze them thoroughly. The material costs are based on prices in research. It can be assumed that prices for industrial applications are considerably

Table 1 Total costs of different maintenance approaches for SMA-AS (in EUR).

Type of cost			Renewal	RC-F	RC-AS	SH-T	SH-E
Material costs	Micro controller		?	?	?	?	0
	Shape memory actuator		1.2	0	0 … 1.2	0	0
	Mechanical structure		?	?	?	0	0
	Periphery	Cable	0.016	?	0.016	0	0
		Joining elements	0.025	?	0.025	0	0
		Housing	0.125	?	0.125	0	0
Service costs	Heat treatment		0.17	0.17	0.17	0.17	0.17
	Adjusting SMA-actuator		0.11	0	0.11	0	0
	Adding connecting elements		0.77	?	0.77	0	0
	Implementation	Demounting	0.07	0.07	0.07	0.07	0
		Replacement	0.03	0.03	0.03	0.03	0
		Mounting	0.13	0.13	0.13	0.13	0
Total cost			**2.63**	**0.39**	**1.43**	**0.77**	**0.17**

lower. Material costs for the SMA-AS without electronic components are around 1.5 EUR. To determine the service costs, an hourly rate of EUR 45 is used. Further, the times for each process are taken 10 times and their average is used for estimating the service costs. Table 1 gives an overview of the total costs. In fields that are application-specific, a question mark is set. These components are not included in the calculation.

Costs confirm the assumptions on the options for a (re-)use of shape memory based actuators by regeneration in Section 4.1. Economical reuse is very attractive. Also, the restoration of the SMA actuator properties through SH is definitely beneficial. Thermally initiated SH can save 0.88 euro, which corresponds to a cost reduction of about 30% for an SMA-AS in maintenance. Cost savings for electrically initiated SH are around 1.11 euro. The repeated use of SH reduces costs even further. However, the reuse of SMA-AS needs to meet the technical requirements, which, unfortunately, is not always the case.

5. Conclusion and Outlook

The paper has investigated the reuse of SMA-AS focusing on "self-healing" properties. Furthermore, the results indicate that the mechanical properties, in particular the displacement, decrease over time, which is due to the functional fatigue. Using "self-healing" can help to restore these properties to a certain degree. The experiments also indicate that the lifetime of SMA-AS cannot be extended due to structural fatigue. The reuse of SMA-ASs can reduce the use of resources and can thus make a contribution by protecting the environment. Nevertheless, as discussed, costs have to be considered carefully, because they are critical if no regulatory constraints are in place.

To use SH in practice, more research is needed. Further studies should, in detail, focus on the important actuator performance indicator like actuator type and dimensions, lifetime, force as well as displacement. Furthermore, various alloy compositions must be investigated, since these are highly relevant. Besides, it is necessary to analyze the question of what constructive measures are useful to further increase effectiveness. This is especially important for electrically initiated self-healing. Finally, it is necessary to run a long-term test of SMA-AS under real conditions.

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