Improving the Performance of Electrically Activated NiTi Shape Memory Actuators by Pre-Aging

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Abstract. Shape memory alloys possess an array of unique functional properties which are influenced by a complex interaction of different factors. Due to thermal sensitivity, slight changes in temperature may cause the properties to change significantly. This poses a huge challenge especially for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators. The displacement is the key performance indicator for the use of shape memory alloys as actuators.

1. Introduction
Shape memory alloys (SMA) have a great reversible elongation with high specific working capacity but also limited dynamics. [1] They have the ability to regain their original shape after a seemingly plastic deformation by heating above a certain temperature. The shape-memory effect was first discovered by [2] in 1932 on cadmium-gold alloys and first described by Vernon in 1941. [3] The most commercially important alloys currently available are shape memory alloys based on NiTi (also Nitinol) discovered by Buehler and Wang in 1963 at the Naval Ordnance Laboratory. [3] The great application potential of shape memory alloys, apart from the medical technology, is still not fully used and SME actuator applications are almost exclusively produced in small and medium series. [4] [5] The main reasons for this are technical aspects such as the limited temperature range of the phase transformation, [6] limited dynamics [3] and challenging SMA manufacturing processes [7] as well as the lack of development guidelines. One reason for their limited use in the context of product design is their behavior under thermal cycling. SMAs show a decrease in the displacement in the first cycles (also known as shakedown) through irreversible plastic lattice deformation and martensite stabilization, [8] which makes the actuator design difficult. Therefore, this paper tries to investigate and meet this challenge.

The paper is organized as follows: The first part provides background information of shape memory alloys and their application fields as well as it describes the shape memory effect. Furthermore, the paper discusses the effect of functional and structural fatigue regarding important actuator performance indicators. Electrical heat treatment is introduced as it is chosen as a method for pretreatment to reduce the shakedown effect. Once the experimental design, which uses the design of experiments, is delivered, the choice of factors and response is thoroughly discussed. This paper
presents the possibility of reducing the shakedown effect of SMA actuators by pretreatment and eludes to future investigations in this field.

1.1. Shape memory alloys and actuators
SMAs belong to the group of active material, also called smart materials. The shape memory effect (SME) is based on a change in crystal structure and microstructure, by which many physical properties change. More precisely, the SME results from a reversible martensitic phase transformation between the cubic high temperature phase austenite and the monoclinic low temperature phase martensite. [9] The phase transformation happens without diffusion and occurs by shear movements without a change in shape, [10] which can be initiated thermally or mechanically. Basically three SMEs can be distinguished, the one-way effect, the two-way effect and pseudoelasticity.

In case of the one-way effect, the material can remember the imprinted form of the high-temperature phase by heating, but not by cooling. [11] It is used for connection, fastening and sealing elements. [10] The first commercial application was a shrink sleeve in the F-14 Tomcat of the U.S Navy for pipe connection in 1971. [12]

In contrast to the one-way effect, the material can remember also a form in the low-temperature phase in case of the two-way effect. [13] There are two types of two-way effects, but only extrinsic technical relevance. [14] The extrinsic two-way effect can be understood as an automatically repeated one-way effect, [15] which requires an external resetting force like a spring.

For the alloys which are based on the two previously mentioned effects, a distinction for applications can be made between the possibility of thermal and electrical activation. [16] Thermally activated SMAs are used as autarchic, self-regulating actuators, e.g. in heating and air conditioning. [17] This type of actuator reacts to a change of the ambient temperature. With electrically activated SMAs, the change in temperature is caused by joule heating. [16, 18] SMA actuators which use this activation are used as positioning elements for a wide range of applications. For this purpose, SMA wires are particularly suitable, since these have a high electrical resistance. [19]

In case of pseudoelasticity, the phase transformation is initiated mechanically. All SMEs have a hysteresis. For pseudoelastic elements, this can be used for damping. [17] [20] The most famous pseudoelastic applications are highly flexible stents, eyeglass frames and tooth tensioners.

1.2. Performance indicators of shape memory actuators with regard to fatigue
A repeated or cyclic use of the shape memory effects of a material leads to fatigue, which limits the functionality and lifetime. [21] The fatigue behavior of SMAs is very complex and multicausal. Important factors in this context include external factors such as: time, temperature, voltage, load and number of cycles, but also internal factors such as alloying elements and composition, the nature of the phase transformation, and the lattice structure. [8] Fatigue in case of SMAs can be distinguished between functional and structural fatigue. [5] [21] [22] Particularly with regard to safety aspects, the fatigue has to be kept in mind when the components are designed. This study investigates the influence of mechanical and thermal stress on this fatigue.

Structural fatigue is understood as the behavior of materials to fail like any material, caused by cracking and crack growth. [8] [21] [23] Functional fatigue covers the changes in mechanical, thermal and other properties by thermomechanical cycles, [4] [21] which is an essential criterion for assessing the stability of the SME. [24] A challenge in the use of SMA actuators is that they first have a shakedown effect before they reach a largely constant operating point. Eggeler et al. demonstrated this effect in a study. [22]

To gain repeatable behavior, which is important for design products using SMAs, it is suggested to use relatively low stress instead of high stress in which case the shakedown would pose a bigger problem. [25] Major findings regarding the shakedown effect are the overload of SMA actuators, which accelerates functional fatigue. [25] Another approach is to limit the displacement of the SMA actuator, which reduces functional fatigue. [26] The authors do not consider possible pretreatment to reduce the shakedown effect prior to use even if it is stated that conditioned SMA wires (actuators) are preconditioned to eliminate the shakedown effect at moderate tensile loads. [25]
1.3. Heat treatment for shape memory alloys by resistance-based heat treatment

The SME is impressed by thermomechanical treatment. Semi-finished SMA products do not have any shape memory properties after the forming. [27] The required shape and functional properties can be adjusted by a separate heat treatment. [28] In addition to the widespread thermal heat treatment by means of a heating furnace, there is also the possibility of a resistance-based or electrical heat treatment based on Joule's heat. The generated heat is the product of the electrical voltage in the electrical conductor and the current. Advantages of this type of heat treatment compared to the thermal heat treatment are the simpler process or construction, and thus a higher process control, lower process time, but also lower energy consumption. [29] [30] Further, partial heat treatment is possible. [27], [31] and [32] have carried out important work on electrical heat treatment.

Like the conventional thermal heat treatment shaping, it is possible to adjust the phase transformation temperatures or to minimize functional fatigue. NiTi typically have a specific electrical resistance of 80 $\mu \Omega \text{cm}$ in the martensite phase and 100 $\mu \Omega \text{cm}$ in the austenite phase, which is comparatively high and thus leads to easy and rapid heating by current. [31] A danger using this type of heat treatment is that it can lead to a slight overheating and associated irreparable damage.

2. Material and methods

2.1. Experimental design

The design of experiments (DoE) is used for this study to identify significant factors and interactions between factors and response. DoE offers a systematical approach with various tools based on statistics, in which several factors are simultaneously changed. Despite the simultaneous change of several factors at a time, clear assignment is possible and thus a disadvantage of the one-factor-at-a-time method, the misinterpretation is not possible. [33] The advantage of this method is higher information quality in contrast to the one-factor-at-a-time experiment, but at the same time less effort. [34] [35]

Based on literature, research and experience, the factors and response are selected. For the response, our analysis focuses on the loss in displacement until stabilization ($\Delta s$), stabilized displacement ($s_{\text{stabilized}}$), the number of cycles until stabilization ($\Delta c$) and lifetime with respect to cycles till crack (c). A visualization is provided in Fig. 1. The selection of investigated factors is based on a cause-effect diagram and further a factor-response-matrix through which the assumed influence regarding the response is evaluated. Based on this, the investigated factors are the type of heating, current, frequency, time and stress during heating. In Table 1, all factors and their levels are listed. A 52 full factorial design is used for the investigation, by which also interactions are determinable. The investigation covers 32 samples.

| factors          | unit | level |
|------------------|------|-------|
| type of heating  | -    | ramp  | step |
| current          | A    | 0.5   | 1    |
| frequency        | Hz   | 1     | 50   |
| time             | s    | 5     | 30   |
| stress           | MPa  | 275   | 400  |
2.2. Experimental setup and material

Due to their practical importance for actuator applications, only SMA wires with a diameter of 150 μm and an alloy composition of 54.8wt% Ni are considered as samples. The samples are crimped at the ends to form eyelets which are used to attach them to the test stand.

A programmable power supply is used for the electrical heat treatment. The sample is clamped in a holder and is loaded by a weight, which is guided by air bearing via a deflecting roller. Crocodile clamps are used for the contacting.

After the heat treatment, the samples are cyclically stressed until they are ruptured. For this purpose, the samples are clamped in two vertical hooks and are loaded by a weight equally to 400 MPa stress. Electrical activation takes place via crocodile clamps, with an amperage of 0.630 A for one second, followed by eight seconds of cooling time. Fig. 2 schematically summarizes the experimental setup, including the components and essential test parameters.

Preliminary tests have also been carried out in which five reference samples have cyclically been activated without electrical heat treatment to be able to compare the influence later on.

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**Figure 1.** illustration of displacement and cycles as response.

**Figure 2.** schematic experimental set-up (left), -components (center) and -parameters of the pre-aging experiments.
3. Results

3.1. Plausibility and completeness
As a first step, a plausibility and completeness check is performed. The criteria of the check for plausibility are the quantiles (2.5 and 97.5). Based on these, an outlier is identified and excluded. The response ranges for the realized cycles between 1306 and 5521 with a mean of 3908. The percentage of the loss in displacement until stabilization ranges between 13.49 and 35.91 with a mean of 21.62. The cycles until stabilization are between 160 and 1100 and have a mean of 543. The stabilized displacement is within a range between 4.051 to 4.684 % with a mean of 4.23 %. Compared to the reference samples, the DoE-experiments have a higher range regarding the responses. The higher range and lower average cycle number until stabilization indicates an effect of the electric heat treatment for pretreatment.

3.2. Effect screening
The first step to analyze the experimental results is a screening, which is illustrated in Table 2. Effects are considered significant regarding a response if the individual p-value is below 0.05. This is equal to a type 1 error (or \( \alpha - \text{error} \)) of 5%. In Table 2 only values meeting these criteria are filled in. Additionally, the half-normal probability plot of the contrast is used for graphical interpretation. The current and interactions are the main influencing factors for cycles till crack. In case of the loss in displacement, the type of heating is another important factor. The time, frequency and stress during heating in the investigated range of factors have no significant impact on the responses. The third-order interaction of current * type of heating * frequency slightly misses the criteria based on the p-value. However, in a graphical interpretation using a half-normal probability plot it becomes highly significant. For the response of cycle until stabilization interactions are exclusively relevant, which is one major indicator and objective of the investigation. One reason for this can be the determination of the number of cycles which can only be done by using graphical methods like a regression analysis and looking up the values from the diagrams. This negatively influences the accuracy and hence the accessibility of factors regarding this response. However, it is certain that the current and type of heating are highly relevant; the parameters of these have to be further investigated. The response of stabilized displacement has similar significances as the cycle and loss in displacement until stabilization.

Table 2. effect screening based on p-value (\( \alpha=5\% \)).

| factor                        | \( c \) | \( \Delta s \) | \( \Delta c \) | \( \Delta s_{\text{stabilized}} \) |
|-------------------------------|--------|----------------|---------------|-------------------------------|
| current                       | 0.0260 | 0.0048         |               | 0.0215                        |
| type of heating               |        |                |               |                               |
| current*time                  |        | 0.0262         |               | 0.0438                        |
| current*type of heating       |        | 0.0016         |               |                               |
| current*type of heating*frequency | 0.0035 | 0.0698         | 0.0088        | 0.0039                        |
| current*type of heating*stress|        | 0.0127         | 0.0564        | 0.0305                        |
| current*time*frequency        |        | 0.0391         |               |                               |
| type of heating*frequency*time| 0.0429 |                |               | 0.0855                        |
| type of heating*frequency*stress| 0.0569 |                |               |                               |

3.3. Discussion
The analysis of the effect of current by linear regression to evaluate the qualitative impact reveals that a higher current leads to a lower number of cycles till crack and to a higher loss in displacement until stabilization but also to a higher displacement after stabilization. If we group the impacts by the type of heating, these effects even increase. An explanation for this is that higher temperatures in heat
treatment and under cycling accelerate fatigue. Due to the fact that the type of heat treatment is a categorical factor, only differences can be recognized (see Table 2). This indicates using step as the type of heating has a tendency for higher loss in displacement until stabilization compared to using ramp.

Regarding the optima within the investigated parameters for the various responses, a distinction must be made between the number of cycles and the reduction of shakedown. For reducing shakedown, other factors, particularly the type of heating, are relevant compared to maximizing the number of cycles. When one response is optimized, interactions may probably not have been considered. The most important difference when optimizing a single response is the type of heating, as can be seen in Table 3.

One reason for this is the fact that a longer lifetime quantified by the number of realized cycles leads to a higher number of cycles until stabilization is reached. If the cycles up to the stabilization are set in relation to the maximum lifetime, it is noticeable that a pre-treatment reduces the shakedown disproportionately.

For the design of SMA actuators, the following conclusions can be drawn from the experiments, which are summarized in Fig.3. For applications which have fewer cycles, the reduction of the shakedown effect by pretreatment can be achieved by at least one third up to two thirds. On the other hand, if a long lifetime, i.e. a high number of cycles is required, the result is a slower stabilization and therefore a higher number of cycles till the SME stabilizes. Furthermore, loss in displacement is higher and the stabilized displacement lower. Therefore, pretreatment is not promising in this case.

**Table 3.** Overview of the optima for the response and their respective factors.

| optima     | factors  | response |
|------------|----------|----------|
|            | type of heating | current | frequency | time | stress | c      | Δs     | Δc     | $S_{stabilized}$ |
| c          | ramp     | 0.5      | 50        | 5     | 275    | 5.566  | 23.71  | 793    | 4.0536          |
| Δs, Δc, $S_{stabilized}$ | step     | 0.5      | 50        | 5     | 275    | 2.942  | 14.81  | 270    | 4.4519          |
| overall    | step     | 0.5      | 50        | 5     | 275    | 2.942  | 14.81  | 270    | 4.4519          |

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**Figure 3.** Qualitative dependency of the response regarding optimization.

**4. Conclusion and outlook**

Even though it is not possible to completely eliminate the shakedown at the beginning of the lifetime of an SMA actuator, with the identified factors, it is possible to reduce the shakedown effect of NiTi SMA wires by electrical heat treatment in a certain range. The study has therefore been able to demonstrate the principal suitability of a pretreatment by electrical heat treatment to obtain stabilized SMA actuator behavior. This makes the material more manageable, which is necessary when designing SMA-based products. The pretreatment is thus an alternative approach to investigations of [25] and [26]. The main factor regarding the pretreatment is the electrical current, but also the type of heat treatment and the profile of current supply which was also indicated by [36] for regular cycling.

**4.1. Outlook**

Further investigations should be performed with larger sample size to further minimize random effects. The low significance of the factors and high relevance of interactions of the third and higher level suggest unconscious effect blending. For this reason, further investigations are necessary. Promising
factors in this context are parameters in use or parameters of the pre-aging procedure using electrical heat treatment, e.g. stress. Alternative experimental designs like response surface plans can be used to investigate the nonlinear behavior of various factors especially the electrical current and interactions.

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