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Strategies for Self-Repairing Shape Memory Alloy Actuators

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Shape memory alloys (SMAs) are thermally activated smart materials. Due to their ability to change into a previously imprinted actual shape by the means of thermal activation, they are suitable as actuators for microsystems and, within certain limitations, macroscopic systems. A commonly used shape memory actuator type is an alloy of nickel and titanium (NiTi), which starts to transform its inner phase from martensitic to austenitic structure at a certain austenite start temperature. Retransformation starts at martensitic start temperature after running a hysteresis cycle. Most SMA-systems use straight wire actuators because of their simple integration, the occurring cost reduction and the resulting miniaturization. Unfortunately, SMA-actuators are only seldom used by constructors and system developers. This is due to occurring functional fatigue effects which depend on boundary conditions like system loads, strains, and number of cycles. The actuating stroke does not reduce essentially during the first thousand cycles. Striking is the elongation of the wire while maintaining the stroke during cycling (walking). In order to create a system which adjusts and repairs itself, different concepts to solve this problem are presented. They vary from smart control methods to constructive solutions with calibration systems. The systems are analyzed due to their effective, life cycle, and system costs showing outstanding advantages in comparison to commonly used SMA actuators.

Keywords automotive, biomaterials, heat treating, mechanical testing, modification

1. Introduction

Increasing automation and miniaturization require an increased employment of actuators based on smart materials. For the selection of these actuators or rather drives, numerous criteria are to be taken into account. Among these, there is for instance the simplicity of the setup, the required space, the kind of activation energy, the speed of the actuation, the reliability and accuracy, the durability, etc. Shape memory alloys belong to the group of smart materials and have the ability to react to an exterior thermal or mechanical stimulus (Ref 1). The most commonly used form is the straight SMA wire. It combines the advantage of simple assembly with simple dimensioning. In spite of the numerous possibilities of using them in diverse technical applications, SMAs are seldom used by design engineers. One reason for this hesitation is the effects of functional fatigue in SMA wires (Ref 2), for which there are no prognosis models or even simulation tools in contrast to the many studies on structural fatigue in other materials. After a certain number of cycles, the wire shows an elongation through which its working position gets slowly dislocated (walking). Moreover, with a growing number of cycles, it suffers a loss of effect which results in the reduction of its maximal displacement in technical applications.

2. Attributes of Functional Fatigue

In general, factors like the displacement and the actuating force as well as the composition of the alloy and the ambient conditions influence the fatigue behavior of an SMA actuator. The most important factors of influence on the fatigue behavior are represented in Figure 1.

If one wants to reach more than 100,000 cycles with the actuator, it is necessary to reduce the available magnitude of effect from a maximum of 8 to 2%. In order to reach such numbers of cycles at all, the only option at current is to use NiTi or NiTiX alloys. However, high numbers of cycles of NiTi converter elements are not achieved from the beginning, as a variety of parameters in the production and manipulation of the material as well as in the construction of the converter have to be considered. Thermomechanical pre-treatments, characterized by cold working, annealing temperature, and annealing time, for example, have a big influence on the stability of the SM effect (Ref 3). Nowadays, an exact adjustment of specific microstructures by the thermomechanical treatment of the actuator material enables a first optimization of the materials concerning the fatigue stability.

Furthermore, two different ways of construction in technical systems, which show the different kinds of functional fatigue are to be distinguished regarding the fatigue behavior. On the

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one hand, a construction form is to be named in which the mechanical load is permanently coupled. For this construction form, the elongation of the SM element and the loss of displacement can be differentiated as forms of fatigue. Here, the reduction of the martensitic stress plateau while maintaining the load is responsible for the elongation. Responsible for the reduction of the stress plateau is the formation of preferred martensitic variants. The cause for the loss of displacement is to be looked for in irreversible plastic strains generated by dislocation motions. On the other hand, it is possible to install a motion stop. The function of the motion stop is to set the force impact on the wire to zero to avoid a force-caused elongation. In contrast to a setup without a motion stop no elongation occurs. Instead a reaction like a bulge of the wire is observed. The reason for this is a kind of training effect (intrinsic two-way effect) caused by cycling with a mechanical load, where the formation of mechanical stress fields in the material affects the formation of defined martensitic variants by cooling. Hence, the low temperature shape is a preferred shape of the martensitic structure. A bulge of this type, however, is not to be ignored and must be considered when constructing SMA-based products by all means, e.g., because the wire can slip off the pulley when a deflection pulley is used. This would cause the entire actuator system to lose its function. The two construction forms are schematically illustrated in Figure 2.

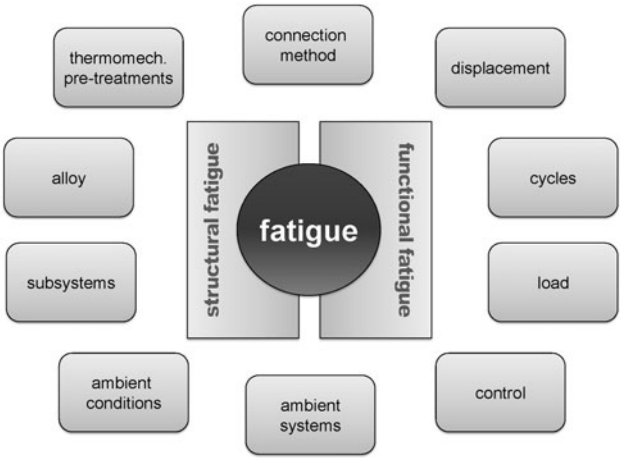

Fig. 1 Influences on the fatigue behavior of shape memory alloys

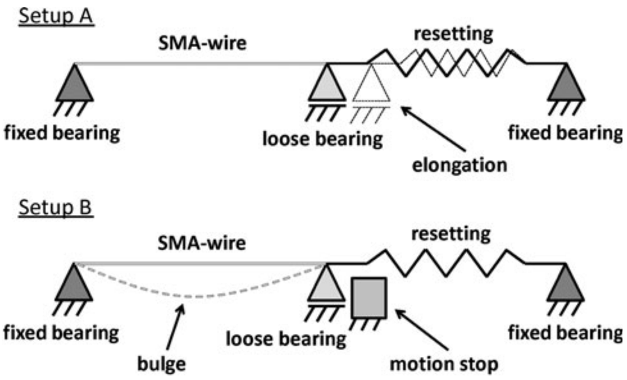

Fig. 2 Possible construction forms and implemented test setups, schematically

In the context of this study, the causes of fatigue are researched and the influences of various parameters on the fatigue behavior are analyzed. Figure 3 shows the resulting loss of the usable strain and elongation to a setup without a motion stop. Here, a wire made of a NiTi actuator alloy was tested. The cold worked wire was annealed 20 min by 400 °C.

3. Experimental Characterization of Material Properties

The experimental analysis can be divided into sections such as thermo-mechanical configuration, tensile test, and functional analysis. NiTi wires with a diameter of 0.2 mm in particular Dy90 and alloy H actuator wires, which are Ti-rich and the alloy S, which is Ni-rich are used for the tests. The displacement is tested as well as the force path and with it the loss of displacement. Depending on the test setup, the dislocation of its working point, the elongation of the wires, or the bulge is tested respectively.

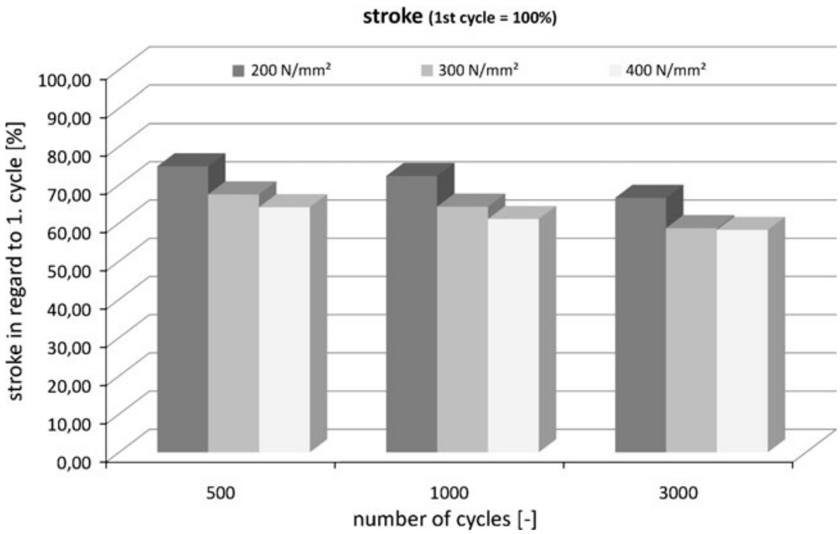

Fig. 3 Functional fatigue (setup A)

3.1 Thermomechanical Pre-Treatment

The modification of specific characteristics of the SMA wires that are poor or Ni-rich, respectively, is caused by thermomechanical pre-treatment. This treatment includes the annealing of cold-drawn wire samples in a furnace (deformation temperature approx. 30%), under variation of the parameters of annealing temperature and annealing time. The annealing of the wire samples takes place between 200 and 700 °C. The annealing time is 20 min.

3.2 Tensile Test

The thermomechanically pre-treated SMA wires undergo the tensile test to determine the relevant functional characteristics of the samples. The tests are executed with changing parameters. These are two different cold worked alloys (S and H) and different annealing temperatures. The samples are strained to 6%. This particular strain is selected because it is still part of the range of the martensitic stress plateau. After the straining to 6% the wires were unloaded and afterward heated. At first, the test determines which SMA effect is caused by the thermomechanical pre-treatment. Under the influence of room temperature in samples of the nickel-rich alloy S the pseudoelastic effect and the thermal effect can occur, for example. Additionally, this analysis determines the rate of the martensitic and/or austenitic plateau stress of the wire samples.

3.3 Functional Fatigue Test

The tests are executed with changing parameters, too. These are pre-stress (200 and 400 N/mm^2), pre-straining as well as test setup. In this case, the pre-straining depends on the load. Due to its modular assembly, all activation tests take place on one test stand. In the tests, each wire is loaded with a constant force and cyclic powered with an electrical current of 0.5 A. The number of cycles amounts to about 3000, one cycle being characterized by 7 s powering time and 14 s cooling time.

3.4 Results of the Tensile Tests

All thermomechanically configured samples undergo the tensile test to specify their characteristics such as type of effect, plateau level, and residual strain. Figure 4 exemplarily shows the results of the tensile test of the S and H alloy samples. Only in the Ni-rich alloy S it is possible to achieve the thermal and the pseudoelastic effect. This is done by shifting the transformation temperatures from an original temperature of 0 °C (A_f-temperature) to 30 °C or 40 °C. The curves of alloy S show this behavior by the clearly dropping of the stress at annealing temperatures of 400 and 500 °C.

The findings of the tests clearly point out the possibility of changing the stress plateau by a change in the thermomechanical pre-treatment and with it in the microstructure of the material. This effect constitutes the basis for "refresh-annealing," during which, with a growing number of cycles, the reduction of the stress plateau can again be compensated by annealing.

3.5 Results of the Functional Fatigue Tests (Comparison Setup A and Setup B)

A comparison between the tests with a motion stop and those without shows that a limitation of the available space has a positive influence on the fatigue behavior (Fig. 5). Figure 5 shows the tests of Dy90 wires.

On the one hand, a constant working point is defined, above which the wire cannot be lengthened directly. Furthermore, it can be shown that the loss of displacement decreases occurs during later cycles. This is a result of the lower strain values caused by the motion stop. As mentioned above, a bulge of the wire can be seen here.

4. Strategies for Compensating Functional Fatigue

In addition, concepts are generated to create a system that repairs itself. As far as possible, these concepts are analyzed according to their efficiency, system costs, and industrial use. Figure 6 gives an overview of over concepts of this sort. In this case, one can generally distinguish between material- and construction-based concepts. The idea of "self repairing" pursues the aim of compensating the existing and inevitable fatigue. This is to say that functional fatigue is not to lead to an impairment of the functionality of the entire system anymore. One advantage of the increased durability that can be achieved in this way is that the employment potential of SMA elements as drive elements in actuators can be increased substantially.

5. Refresh-Annealing

Refresh-annealing constitutes one of the most important concepts within the self-repairing strategy. This concept does

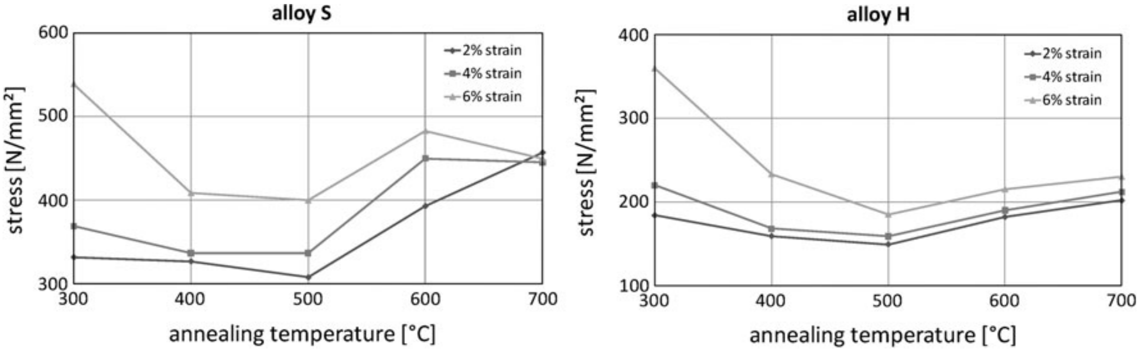

Fig. 4 Distribution of stress of the 20 min annealed samples

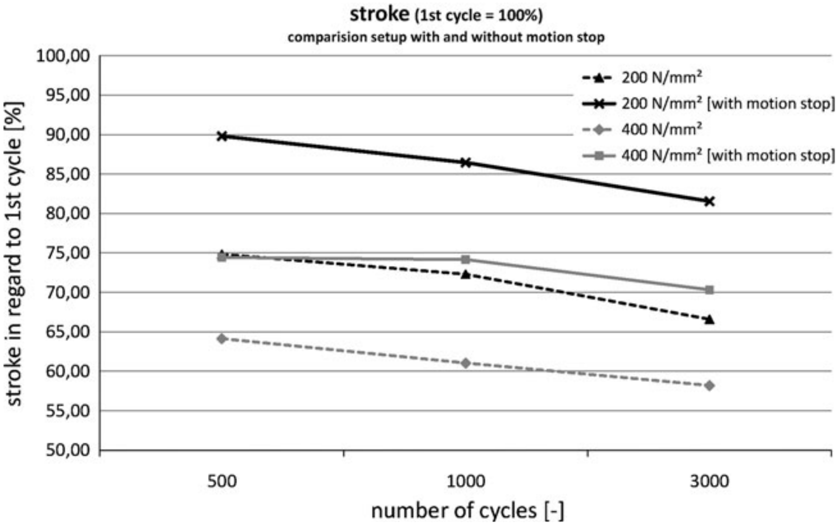

Fig. 5 Comparison setup with and without a motion stop

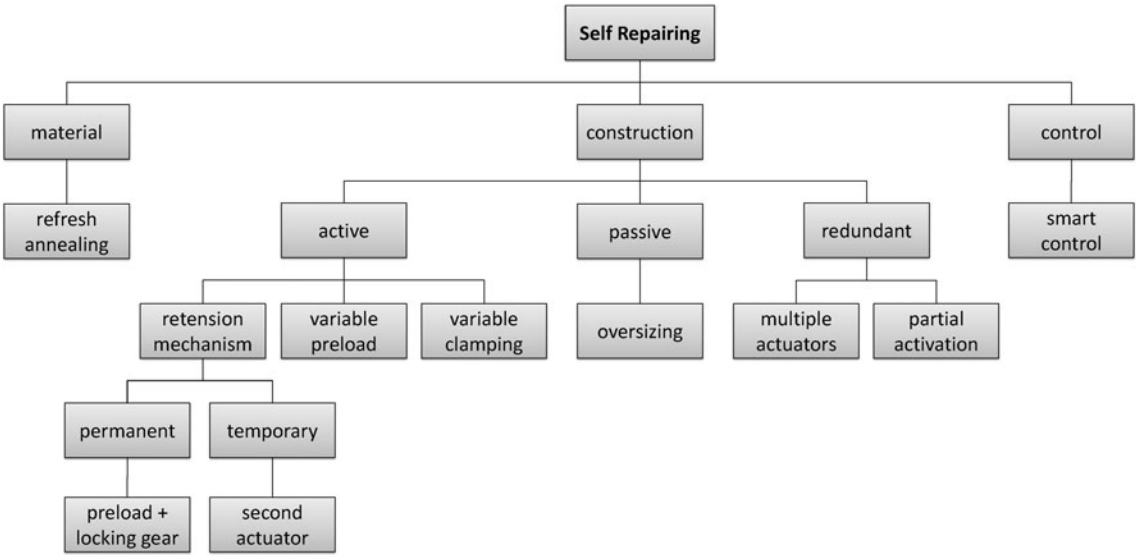

Fig. 6 Overview over concepts for implementing the "self-repairing" strategy

not require any additional mechanical components and therefore presents a simple and inexpensive possibility to optimize the fatigue behavior. Here, the wire is annealed yet another time after reaching a previously determined fatigue-caused elongation, in such a way that a further drop of the stress plateau is prevented. In this process, the cycle is stopped and the loaded force decoupled. In the stress-free assembly, an annealing process which raises the stress plateau up to a prior level can now be executed. One problem of this concept is the change of parameters like the transformation temperature, which can be seen from the longer cycle time. This problem can be tackled by a regulation of this process via resistance control (Ref 3).

5.1 Results of the Tensile Tests of the Refreshed Wires

The results of the tensile tests of the samples (Fig. 7) of a refresh cycle clearly indicate that the descended stress plateau (here: the martensitic stress plateau) can be raised again with the help of annealing. The annealing is carried out at a temperature of 250 °C. The objects of examination are wire samples of an actuator alloy in different phases of the refresh process. The first curve is constituted by the original state of the wire. The cycling of the wire then represents the second curve and the resulting fatigue. The third curve comprises the annealed wire, which is cycled again in the fourth curve. The curves are normalized to the zero point. So the plastic strain is faded out.

5.2 Results of "Refresh-Annealing"

As a result, we can record the samples that are annealed at the relatively low temperatures of 200 and 250 °C exhibit the best refresh behavior. This refresh process almost reaches the original quality of the material. Besides, the low annealing temperatures can ensure that a refresh process of a SMA element can take place while it is integrated. Thereby, the technical operationality is greatly improved. Figure 8 shows the outcomes of the tests on refresh-annealing. In these, it is clearly noticeable

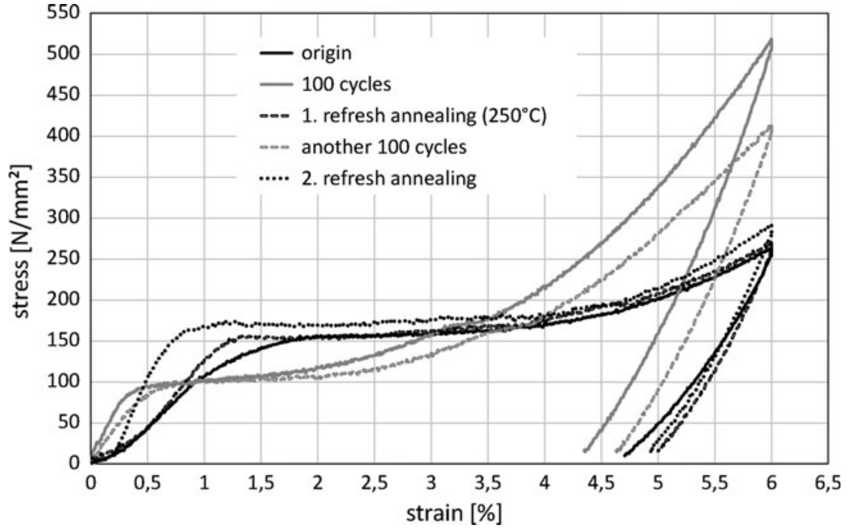

Fig. 7 Tensile tests curves of the sample wires in different refresh phases

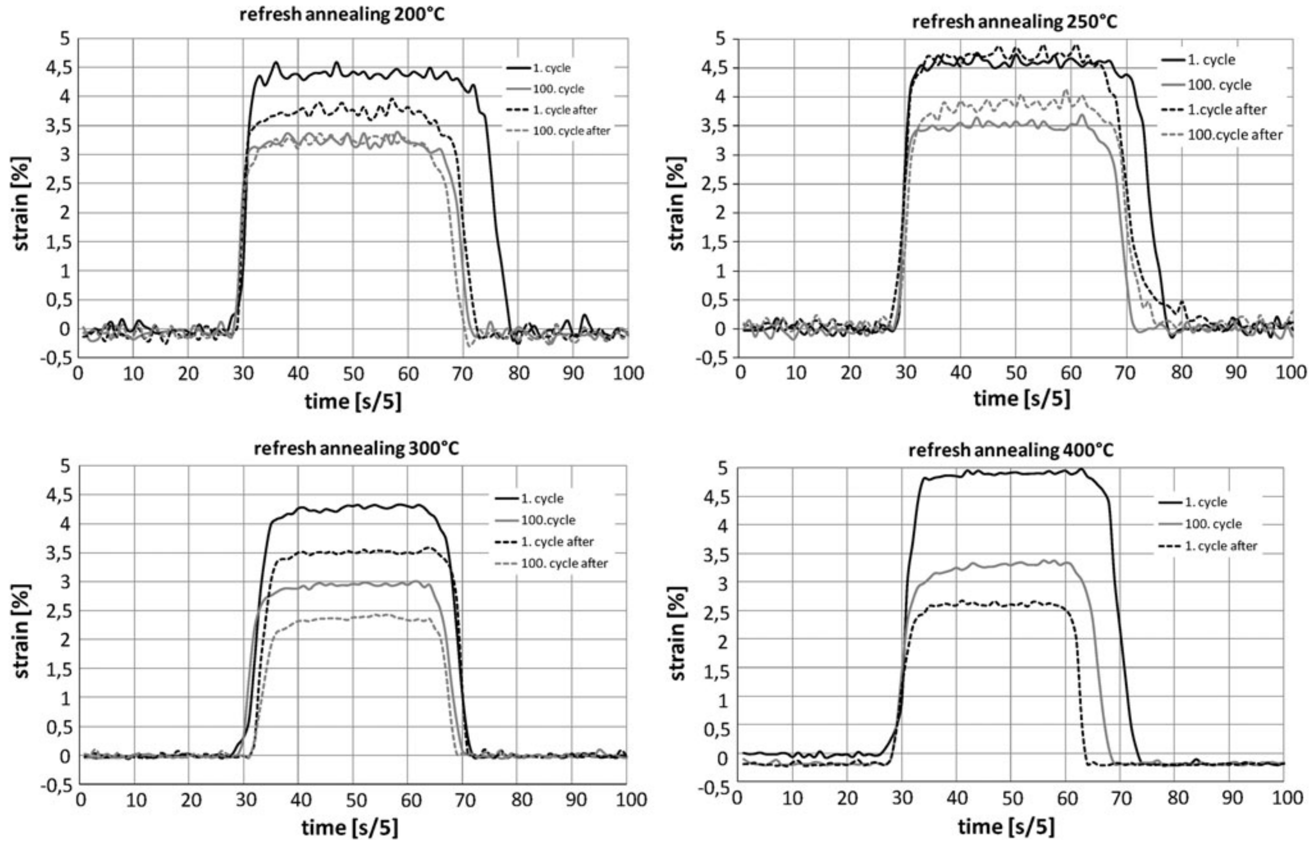

Fig. 8 Refresh-annealed wires, annealing temperatures 200 to 400 °C

that it is possible to convert the remaining strain into a usable strain again. Even after multiple cycles, the refreshed samples display a fatigue behavior that corresponds to the original state. Moreover, the tests demonstrate that an increase of the annealing temperature leads to a deterioration of the refresh behavior (Fig. 8). Annealing temperatures of over 400 °C do not show any refresh effect anymore, but rather cause an accelerated fatigue behavior. This may be due to regeneration processes, since the decrease of the dislocation density causes the SMA effect to lose stability in the known way.

300 thousand cycles can be realized with the refresh-annealing method. This comes up to 300% of the maximum durability of conventional SMA-components at the same boundary conditions. In this test, the wire was loaded with 200 N/mm^2 and pre-strained with 4%. Figure 9 shows the results of the durability test.

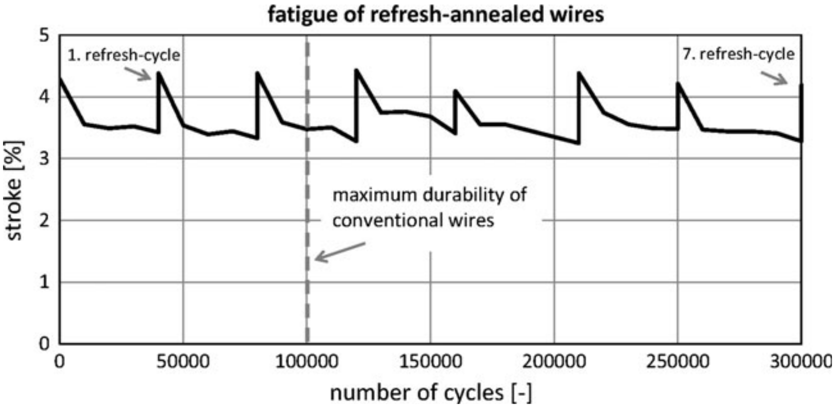

Fig. 9 Durability of refresh-annealed wires

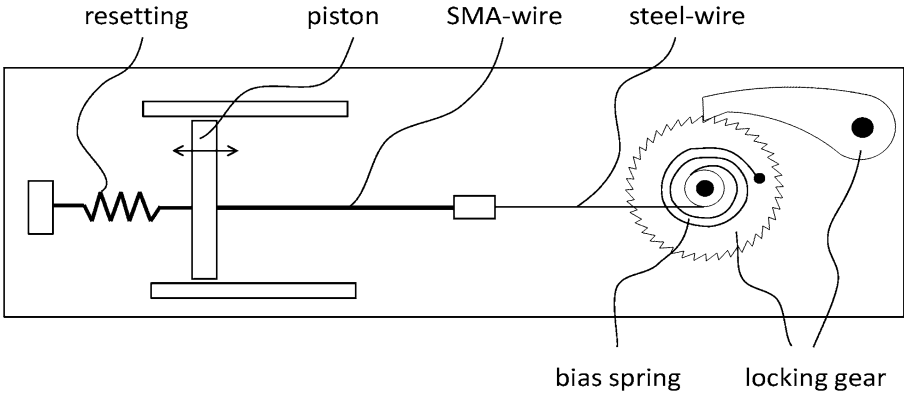

Fig. 10 Concept to tauten the wire

6. Mechanical Adjustment

A further possibility to compensate for the functional fatigue and the resulting loss in displacement could be realized by a mechanical adjustment system (Ref 4). This means that the wire would again be tautened about the amount of its elongation to its tight condition after every cycle. A first model of such a reset mechanism, which is to compensate the bulging of an SMA wire independently, is shown in Figure 10. Here the wire is connected with a gear pre-stressed by a spiral spring. The backward motion of the gear is prevented by a locking mechanism. The condition in this case is that the stress of the wire is significantly below the martensitic plateau. The presented concept is representative of a multitude of possible scopes for design. Only by suchlike constructions can the bulging of a wire be effectively compensated and the reliability of the actuator system is enhanced.

7. Conclusion

On the one hand, in this study different fatigue mechanisms could be clarified. On the other hand, it has been shown that it is possible to balance out the losses in function and displacement of an SMA component. At the same time, different concepts can be distinguished, which are yet again tailored for particular kinds of fatigue. In this way, the durability of SMA actuators in technical applications can be further increased.

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