

Impact of Different Electrical Time-Based Activations on NiTi Shape Memory Alloys

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Abstract. The use of NiTi shape-memory alloys (SMA) in actuators bears significant advantages for designing robust, simple and lightweight applications. The SMA effect is based on a phase transformation of the atomic lattice in response to stress, strain and temperature. The resulting crystallographic configurations lead to a complex behavior revealing different electrical and mechanical characteristics. In view of the impact of thermo-mechanical cyclization on the operational lifetime, this paper investigates the influences of different types of electrical activation. For this purpose, six current curves with six samples each are compared to a reference activation with regard to the operational lifetime. The chosen time of activation is 1 second in accordance with an industrially relevant cycle of technical actuators. Based on the results of these investigations, recommendations of the activation type shall be developed for the operational lifetime of NiTi-SMA.

1. Introduction

Smart materials (SM) like shape memory alloys provide many advantages for the design of cross-industry technical products such as their energy saving potential (in Germany) of about 16TWh/a as well as their emission saving potential of about 8t CO₂/a [1]. Furthermore, they offer a great potential for developing lightweight and miniaturized actuators and sensors, while also reducing the complexity of technical actuator assemblies [2, 3]. Despite these advantages, the impact of shape memory alloys on the global market is still very low. Smart material applications for motors and actuators have a market value of USD 26 billion with a compound annual growth rate (CAGR) of 10.2% (between 2014 and 2019) instead of the predicted 15.8% (between 2011 and 2016) [4, 5]. This 5% reduction of the expected CAGR in the new study clearly shows the difficulty of smart materials to grow in the global market. Comparing the advantages of SMAs to their relatively low market value unveils certain problems with the developing process of SMA actuators. This is based on the complex relationship between stress, strain and temperature and, as a result, the electrical and mechanical characteristics that limit the handling for engineers and scientists [6].

Due to their fast and time-controlled activation with simultaneously usable sensory features, electrically activated NiTi SMA will have a huge significance in the future. [7] This is particularly true for cyber physical systems [8] as a result of the increasing amount of sensory-recorded information in technical systems and the possibility to keep the complexity of technical systems low. [9, 10]

In regards to electrically activated SMAs based on NiTi, many investigations focus on medical pseudo-elastic applications [11, 12, 13], sensory features [14, 15, 16] as well as thermal heat treatments. [17, 18] Furthermore, electrical activation were researched in connection with the positioning control and activation control. [19, 20] This has become particularly important for many



technical applications. However, the biggest application field for actuators in technical systems is the simple time-controlled actuation. This is based on the historical evolution of mechatronics (relay-circuit, Programmable Logic Controller [plc]), which realized only two positions/ functions (0 and 1). [21] SMA actuators are a good substitute for an electromotor for a variety of applications, such as a door locking device and can be directly integrated with existing electrical control systems. [22] Unfortunately, this time controlled activation has hardly been scientifically researched yet. [23, 24, 25] An approach to lower the market entrance barriers for SMA applications has been realized by [26] in accordance to [27] by using a cross-impact matrix of SMAs in order to analyze the influences among each other. One of the essential findings is that the operational lifetime as well as the activation frequency are interdependent. Due to the fact that in the thermo-mechanical cyclization the type of energy input has as well a substantial influence on the operational lifetime [28, 29, 30], this paper shall especially investigate the type of current within the determined and relevant time-controlled cycle time for technical actuators. The cycle time is set to (up to) 1s. [21] Based on this aim, the following four parameters are used as the main focus of this investigation:

1. the activation time
2. activation by means of current
3. course of the activation
4. operational lifetime until the rupture:

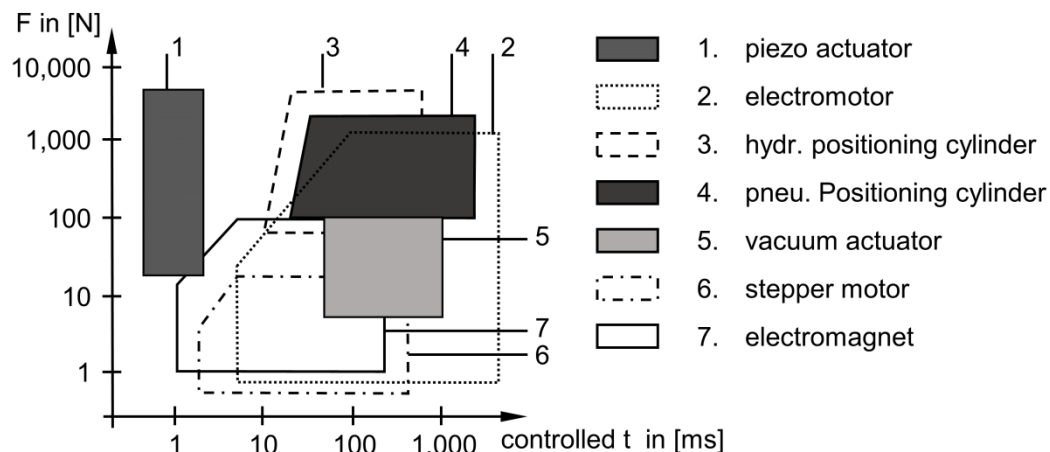


Figure 1. force – actuation time (controlled) for common actuators [21].

2. Experimental Setups, Material and Methods

2.1. Introduction

Ten reference tests are run in order to make a valid statement about the type of current that has the greatest impact on the operational lifetime. For this purpose, conventional rectangular current curves are used for the activation. [24, 28, 31] This and the following activation parameters of the reference were chosen according to a control strategy in which reaching the austenite finish point represents the end of the cycle. [16, 24] These preliminary tests serve to determine a standard deviation, which represent the calculation base for the required individual tests. Different curves for electrical activation are then selected and researched in the following test series.

2.2. Material and Experimental Setup

All presented tests make use of the economically significant and commercially available binary nickel-titanium wires by SAES Getters Company. The wires of Smartflex® SF90 (54.8wt% Ni) exhibit an austenite finish temperature of 90 °C. Activated wire lengths of 100mm with a wire thickness of 0.3mm are used in all tests. All wires of this test series are cyclically activated for 1s and cooled down for 9s in a room temperature of 23 °C (stationary air) with a mechanical load of 400MPa. Moreover, the tests prescribe that only the samples with a contraction of 5% are considered as completely activated and will be taken into account. The test samples are cycled as long as the wire rupture takes place.

The testing facility consists of five vertical pillars in order to perform five parallel tests. The wires will be activated by a programmable laboratory power supply. For this purpose, the samples are provided with a crimped loop at the end of the wire and are hooked into the designated positions that are presented in figure 2.

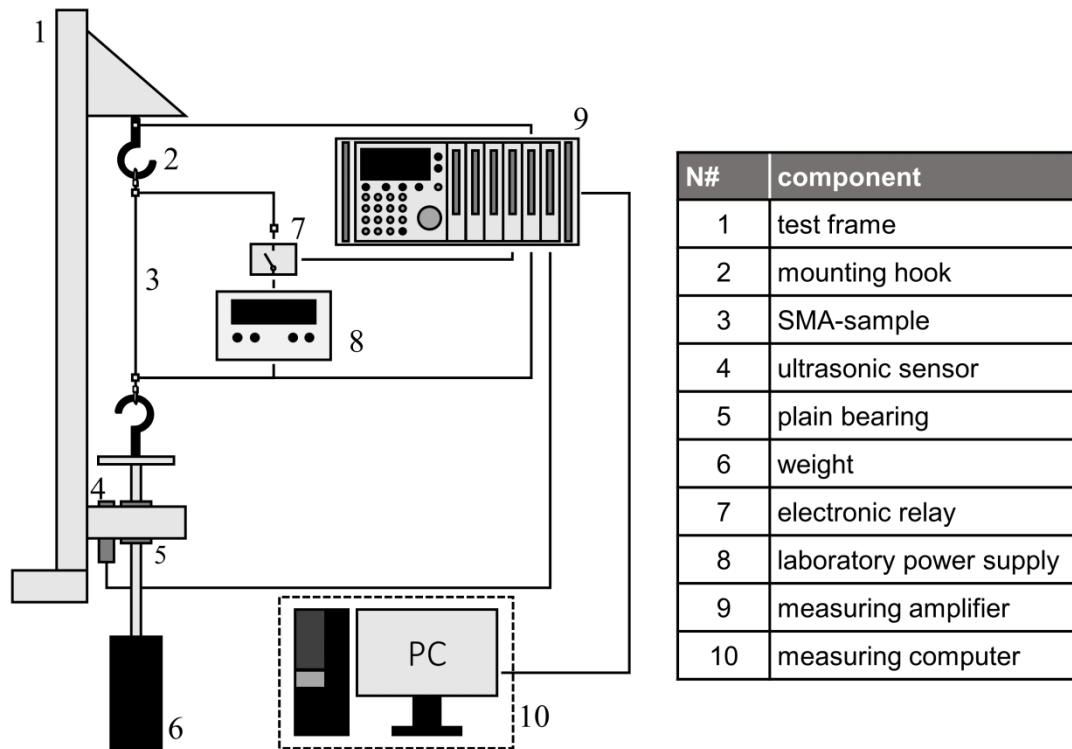


Figure 2. schematic experimental set-up and components.

2.3. Design of experiment

This investigation is based on a method which uses the “standard deviation” of $\sigma = 476.1$ cycles (taken from an already performed sample) and the “technological relevance” $\Delta\mu$ to calculate the lowest experimental effort. [32, 33] With this minimal requirement, it is possible to find a statistically relevant distinction with a probability of 90%. The total amount of the measured values can be calculated with the following equation:

$$\text{Scope of Experiment} \quad N = 60 \cdot \left(\frac{\sigma}{\Delta\mu} \right)^2 \quad (\text{Eq. 1a})$$

The technological relevance $\Delta\mu$ amounts to approximately 580 cycles and has been derived by the experiences of performed durability tests of electrically activated SM actuators. By means of both, the values of the standard deviation and the technological relevance, the total amount ‘N’ of the required measured tests are calculated as part of the next step:

$$N = 60 \cdot \left(\frac{467.1}{580} \right)^2 = 38.91 \quad (\text{Eq. 1b})$$

2.4. Tests

39 measurements are required to investigate seven types of current in relation to the operational lifetime. These 39 measurements, as said in [32], are divided into the 7 types of current, which results in 6 samples per test series.

Figure 3 schematically shows the current curves for the further operational durability tests. As there are no scientific investigations in this field, these current curves have been chosen freely. They have been selected with the objective to provide a reduction of current in a cycle, to cover different types of ramps/platforms as well as to investigate dwell times as seen in curve b) and d) of 150ms within a

cycle. While the current curve e) performs a complete sinus curve, the curve f) performs only half a sinus curve within the same time. All six current types are now compared with a rectangular activation reference.

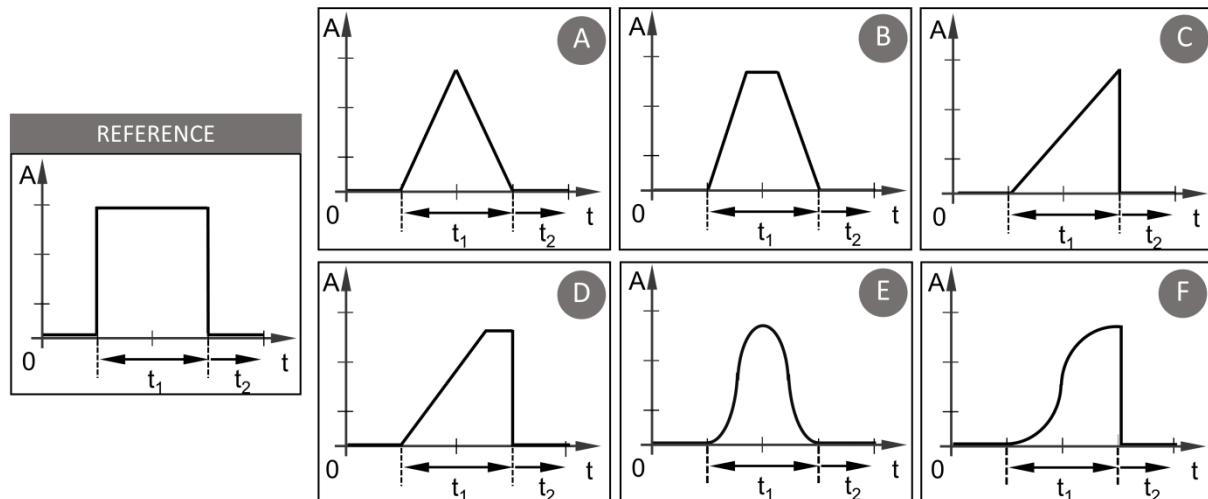


Figure 3. Schematic diagram of the current curves (A) rectangular, (B) trapezoid, (C) saw-tooth, (D) saw-tooth plateau, (E) sinus, (F) sinus-saw-tooth.

Table 1 shows both the investigated currents of the preliminary tests and the relevant parameters for the endurance tests such as the measurement frequency, the absolute time for one cycle as well as the mechanical tension. The electrical current which is used for the rectangular activation is comparable to the current of the electrical controlled activation.

Table 1. Summary of parameters for the tests

Type of power	<i>rectangular</i>	<i>triangle</i>	<i>saw-tooth</i>	<i>saw-tooth-plateau</i>	<i>trapezoid</i>	<i>sinus</i>	<i>sinus-saw-tooth</i>
current	2.35 A	3 A	3.2 A	3 A	3 A	3 A	3 A
measurement frequency	50Hz						
activation time	1s						
cooling time	9s						
absolute cycle time	10s						
mech. stress	400MPa						

2.5. Results and discussion

As illustrated in table 2, the criterion for the technological relevance of $\Delta \mu = 580$ cycles has been fulfilled. This means the deviation of all cycles is higher than 580 cycles to the reference. As a result of the proved technological relevance, there is a considerable influence of the selected activation current on the operational lifetime.

Table 2. Summary of all average values from the tests

Type of Power	<i>triangle</i>	<i>sinus</i>	<i>trapezoid</i>	<i>rectangular</i>	<i>sinus saw tooth</i>	<i>saw tooth</i>	<i>saw tooth plateau</i>
average cycles till crack	15.349	11.590	8.483	7.487	6.695	5.949	1.299
max. displacement (mm)	4.99	5.15	5.20	5.44	5.31	5.30	6.67
min. displacement(mm)	2.52	2.90	3.15	3.22	3.35	3.39	4.19
max. displacement (%)	5.02	5.16	5.25	5.48	5.31	5.35	5.38
min. displacement (%)	2.53	2.90	3.17	3.25	3.35	3.42	4.19

lost in displacement absolute (%)	49.60	43.80	39.62	40.69	36.91	36.07	22.12
elongation (%)	3.20	3.87	5.47	7.75	6.20	9.35	20.03
change of operation point (mm)	3.29	4.02	5.74	8.36	6.60	10.23	25.14
min. elec. resistant martensit (Ω)	1.75	1.67	1.71	1.74	1.68	1.72	1.70
max. elec. resistant martensit (Ω)	1.79	1.74	1.85	1.95	1.84	1.99	2.56
min. elec. resistant austenite (Ω)	1.47	1.45	1.44	1.46	1.40	1.45	1.41
max. elec. resistant austenite (Ω)	1.71	1.65	1.73	1.81	1.70	1.82	2.17

The test series with the activation current “saw tooth plateau” has achieved the worst results on the operational lifetime of average 1,299 cycles but the highest possible displacement of $s = 6.67$ mm and a minimal displacement of $s = 4.19$ mm. The wires have been predetermined with a displacement of 5%, which amounts to 5 mm. The effect of a displacement of over 6.6% indicates a great elongation of the wire which compensates the displacement loss. In comparison, the current method with the triangle curve has achieved the highest cycle number on an average of 15,349 cycles but the least maximal and minimal displacement of $s = 4.99$ mm and $s = 2.52$ mm.

The measurement results show that a symmetrical current curve with an increasing and decreasing course in the activation cycle has a positive influence on the operational lifetime. Furthermore, the measurement results demonstrate that the conventional activation of wires with a rectangular curve has the least operational lifetime expectation of all symmetrical types of activation.

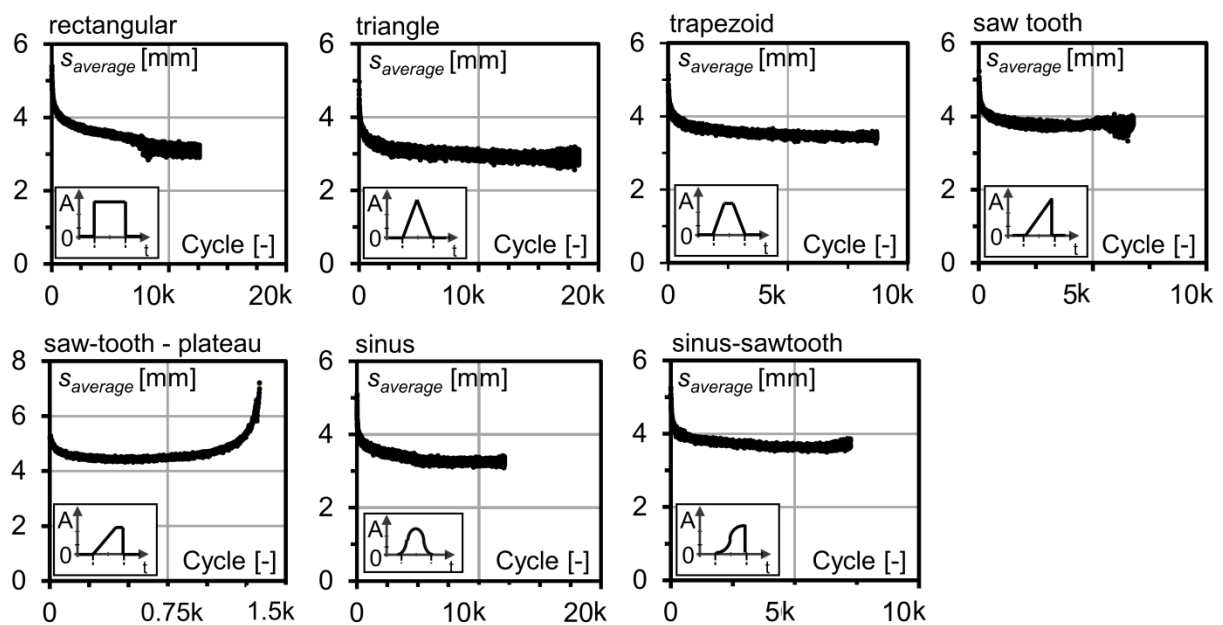


Figure 4. average loss of displacement over the operational lifetime.

Figure 4 shows the average loss of displacement. In every diagram, the six curves of the test procedure superpose each other. One exception is the larger number of cycles compared with table 2 observed in the rectangular, triangle and saw-tooth graphs.

2.6. Discussion

The investigations were able to determine significant statistical distinctions regarding the type of current within the time-based activation frequency that is relevant for technical actuators. [21] The limits of the sample are a contraction of 5%, an electrical activation time of 1 s as well as a mechanical tension of 400 MPA when using SM wires with a diameter of 0.3mm. This research has investigated seven different types of current (time-controlled) with six single tests in relation to their influence on the operational lifetime. The results have shown substantial distinctions in comparison to the standardized electrical activation [24, 28, 31] by means of rectangular current course. Symmetrical current curves and especially the triangle curve, which provides an increase and a decrease of current within a cycle, has shown an operational lifetime of 15,349 cycles, which corresponds to a double operational lifetime in comparison to the reference (rectangular current). In this context, they have nevertheless shown the greatest effect in the loss of displacement of 50%.

In comparison, the current curves with increasing current, which present their maximum at the end of the cycle, deliver the worst results. The number of cycles is significantly below 10,000. However, this type of current, especially the “saw tooth plateau”, demonstrates a strong change of the elongation of about 20%. This elongation compensates the loss of displacement and leads to a higher displacement at the end of the operational lifetime. This investigation has also shown that the criterion for electrical controlled activations by reaching the Austenite finish temperature with a rectangular current is not sufficiently accurate. In comparison to other forms of activation especially the triangle form revealed that the fatigue of the SMA is accelerated by the electrical current. This leads to the assumption that the electrical current has an additional but not further specified effect on the regular fatigue based on the thermo-mechanical cyclization.

3. Conclusion and outlook

The investigations show that an adjusted time-controlled current with comparable parameters can crucially influence the operational lifetime of NiTi-SMA. With this investigation, it is possible to find operational lifetime-optimized currents for an activation of 1s for technical applications.

As a result of the investigations, it is seen that the electrical current / the electrical activation by using comparable parameters has an additional effect on fatigue and lifetime of SMA.

3.1. Outlook

In further investigation will need to carry out a higher number of tests, which goes beyond the statistical minimal requirement, in order to reduce the influences of material scatter and the scatter of prepared samples even further. In addition, further tests with different mechanical tensions and temperatures should be performed in order to newly evaluate the operational lifetime of alloys in relation to the current, especially in comparison to the existing manufacturer's specification. It is further recommended to investigate additional current curves and their influence on the operational lifetime.

4. Acknowledgment

The authors acknowledge the funding of the FLAAI project through the aviation research program LuFo V-1 by the Federal Ministry of Economic Affairs and Energy.

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