Concept development for a test rig and analysis of the experiments for standardized testing of shape memory alloys.

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Abstract: This paper presents the concept development of a standardized test rig as well as the corresponding test plans which takes into the consideration as many as possible parameter of influence on smart materials. For this purpose, the design of the test rig itself, as well as the design of experiments and the analysis of the achieved results based on various statistical methods is discussed in detail. The main challenge of this concept is the development of a system which will lead to a significant reduction of the development time during the product development process of shape memory actuators.
The realization of the concept (design of experiments, analysis of the results as well as the prognosis of the lifetime) is shown exemplary on selected life span variables. For the sake of completeness, the design of the corresponding test rig as well as its functionality are discussed in detail. Finally, the achieved results are described regarding the applicability and show the possibilities of further development of the actuators.

Keywords: Smart materials, Shape Memory Actuators, Testing, Design of Experiments, Descriptive Statistics.

1. INTRODUCTION

There is a wide range of application concepts which have been provided in the previous years for smart materials. Based on these concepts, enormous potential of the shape memory actuators has been proved for many times. According to this fact, shape memory actuators transformed from a niche to a series product which in the meantime became at least of equal value compared to the conventional (electrical) actuators. However, this kind of technology is still categorized as novel and unconventional. A large-scale implementation of shape memory actuators failed because of missing, standardized and homogeneous testing equipment and testing plans based on the application of appropriate load spectra which would provide reproducible results. Especially a replicable determination of fatigue behavior, service life, degradation and reliability of shape memory actuators is not possible and has to be analyzed.

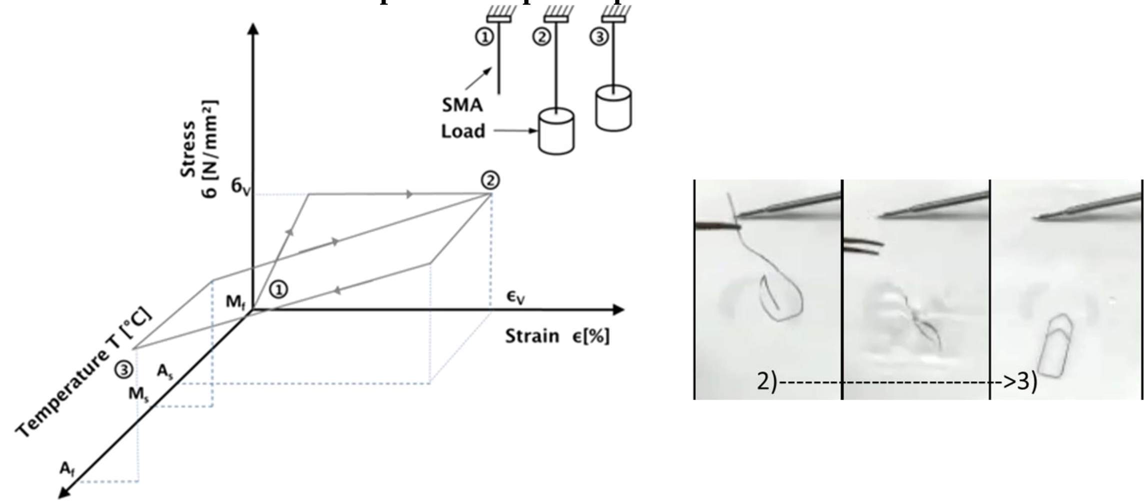
A further issue during the development of products based on the mentioned technology, is the development time with regard to the expected lifetime, which in many cases is much too high, especially for small and medium enterprises. For example an actuator, which shall resist at least 250.000 cycles may take several months of testing in case of smart materials and only several days for an equivalent electromagnet.

2. FUNDAMENTALS OF SHAPE MEMORY ALLOY ACTUATORS

Shape memory alloys (SMA) are smart multifunctional materials which exhibit the remarkable property to recover a previously imprinted shape after a mechanical deformation. The transformation effect, relies on the martensitic phase transformation [1]. During heating the material transforms from the low temperature phase (called martensite) into the high temperature phase (called austenite) by exceeding the austenite start temperature (A_s). This is linked to a shape change ending at the austenite finish temperature (A_f). The heating can be achieved by thermal fields or by electric heating utilizing the Joule's effect.

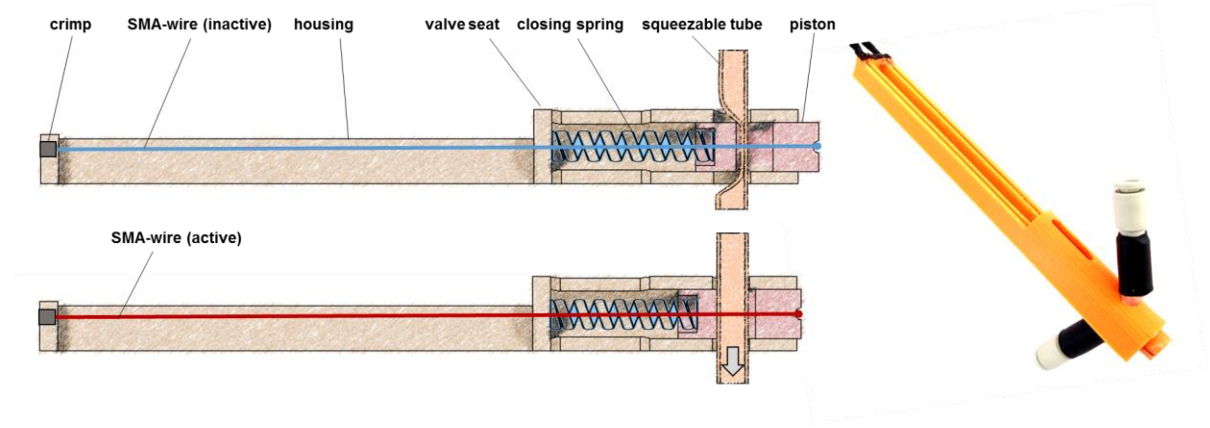
During subsequent cooling, the reconversion of the material is provoked by the retransformation from martensite start temperature (M_s) to martensite finish temperature (M_f). The effect can be used in order to generate mechanical forces and displacements, known in the field of mechatronics as actuations. Most commonly used shape memory materials are binary nickel titanium alloys (NiTi), consisting nearly of a 50 % ratio of both elements. The ratio is the crucial factor for setting up transformation temperatures. Figure 1 shows the transformation characteristic with a simple SMA actuator pulling a mass during heating. These intelligent materials have certain characteristics which are unique in comparison to other actuating principles. A striking advantage of SMA is the significant higher working capacity in comparison to conventional actuators. A shape memory alloy wire actuator with a diameter of 2 mm is able to lift a weight of 120 kg by a self-weight of just 25 g. Furthermore, shape memory actuators make noiseless actuation possible, which is desired especially in automotive comfort-applications.

Figure 1: (left) schematic characteristic of SMA two way effect, (right) example of SMA material with imprinted shape and placed in 80°C hot water



Today's SMA actuators can be found e.g. in small valves in automobiles [2], auto-focus systems in mobilephone-cameras [3] and thermal regulators for building automation [4]. Earlier publications [5] presented valve drives like the quench-valve. In this application the SMA wire quenches a flexible tube affecting the flow control of the fluid.

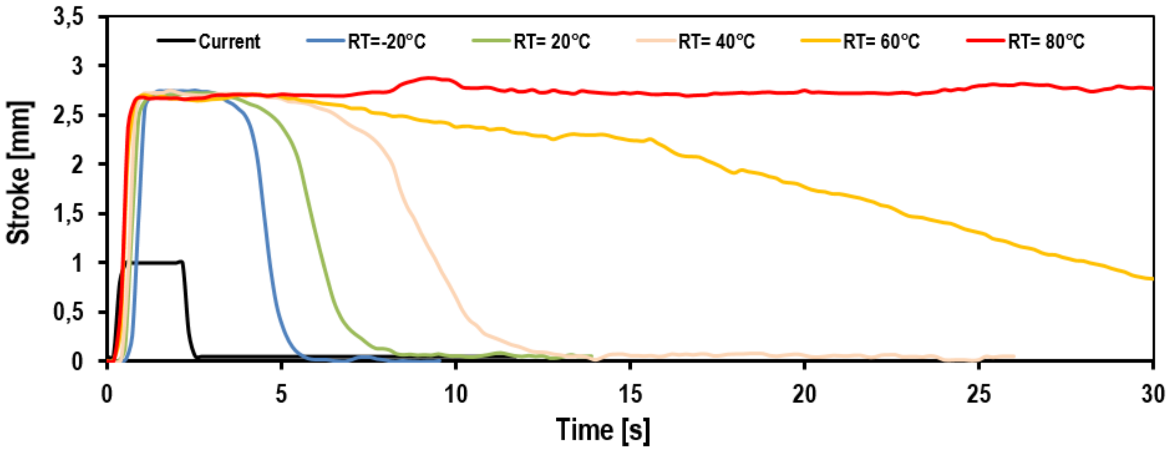
Figure 2: SMA actuator quench-valve: if the SMA wire is cold, the mechanical pressure spring quenches the tube blocking the fluid in it (upper left). If the SMA wire is activated by electrical current it is stronger than the mechanical spring and the tube terminal is opened (lower left). Photo of the quench valve demonstrator (right)



While there are striking advantages of SMA actuators concerning miniaturization and simplification, the development-time of SMA actuators is one of the major obstacles in this field. Due to the thermal characteristic, the resetting time of an SMA actuator corresponds the cooling time from the A_f to M_f

temperatures. Hence, the cooling time depends on the thermal balances of the SMA actuator itself, the ambient thermal field and the thermal characteristics of the actuator mechanical parts (for example: housing). An exemplary experiment result is shown in figure 3 as a stroke over time diagram at different boundary conditions. The used SMA element is a NiTi49.8 alloy in wire form (diameter 0.2 mm, length 150 mm). At ambient temperature of 20°C the actuator is triggered within 1 second, and cools down within 10s if it is reseted by a tensile stress of 200 N/mm^2. If the temperature rises to 60°C, the difference between the retransformation temperatures and ambient temperatures are significantly lower which causes a slower resetting time of 17 seconds. If a fatigue test of such actuator has to be done, a cycling of the actuator of more than 250.000 cycles has to be planned. By a cycle time of 11-18 second per cycle, such an experiment can take even 31 to 52 days. If an SMA wire has a bigger diameter, the resetting time rises with a quadratic characteristic. All in all, SMA fatigue tests are vital for product development due to nearly unpredictable behaviour [6] and lack of standardized modules [7].

Figure 3: stroke over time behaviour of a SMA element as a function of temperature



The fatigue of shape memory alloys itself can be seen as a multiclausal phenomenon parting into:

- Effect-fatigue, which is caused by the cycle-dependant extinction of dislocations within the material [8]
- Mechanical fatigue, resulting from inhomogeneous thermal profiles over time. If the SMA actuator is only partly transformed during heating and cooling phase, the cooler actuator's parts are elongated. This elongation leads to necking and finally to mechanical failure.
- Thermal caused overheating. The overheated parts of the actuator can become more ductile, also leading to necking, and mechanical failure.

All these fatigue-parts depend on engineering parameters of SMA actuators like used stress-strain level of the SMA element, the control strategy, the mechanical load characteristic and material parameters like Ti-ratio and thermomechanical heat-treatment [9].

In order to analyse the fatigue behaviour, the recording of stroke performance over time during cycling is a common method which is focused in this publication. Earlier studies proved also the possibility to measure the resistance of the material in order to calculate the condition of the SMA actuator and it's fatigue [F10-SMASIS15]. While the first cycle reaches a displacement of 4% of the SMA wire's length, the same wire only reached 2.9% after 2.000 cycles. With this it is possible to get a function between stroke performance and fatigue and the lifetime of the SMA wire can be forecast.

3. EXPERIMENTAL SETUP FOR TESTING OF SMART MATERIALS

In order to analyze the performance of SMA wire actuators, a test rig as presented in figure 4 (left) is used. It is configured to test three SMA specimen at the same time. The specimen (for example 2) are mounted to fixed bearings (1) on one side and to a moveable bearing (5), which can slide along a defined track (3). The connection of the SMA wired with the test rig is done by clamps (4) which are normed by VDI2248 guideline [VDI2248]. A stopper (6) ensures that the specimen will not be elongated additionally to the first deformation of the SMA elements which has to be done every time during preparation of the experiment. The mechanical loads (7) are of major importance to the fatigue behavior. In this experimental setup the tensile loads of 100 MPa, 200 MPa and 300 MPa have been adapted to the channels A, B and C of the test rig. The test rig is mounted on an aluminum frame (8). The stroke of the SMA wires is measured by potentiometric sensors (13) and recorded by a measurement-amplifier (11). The amplifier also measures the voltage levels of the specimen during heating phase at constant current levels supported by the current source (10). A linear switching unit (9), which is steered by the computer terminal (12) sets current levels on the SMA specimens on the rig.

On the right sight of figure 4 an experimental result is given for an SMA wire class of 0.4 mm diameter and an initial length of 120 mm. The specimen have been elongated at 2.5% strain. The test has been performed at 20°C with three specimen at 100 MPa, 200 MPa and 300 MPa tensile loads. Due to the material characteristic of SMA, the phase transition temperatures increase with higher mechanical load levels. If the thermal difference between the ambient temperature and the transition temperatures is high, the SMA cools down faster. This explains the variation of the resetting curves. The mechanical load has also influence on the activation, which has been automatically compensated by the test rigs logic in order to ensure comparable data with SMA triggering time of one second.

Figure 4: (left) schematic of the lifetime performance test rig, (right) one cycle of three specimen at different mechanical load levels.

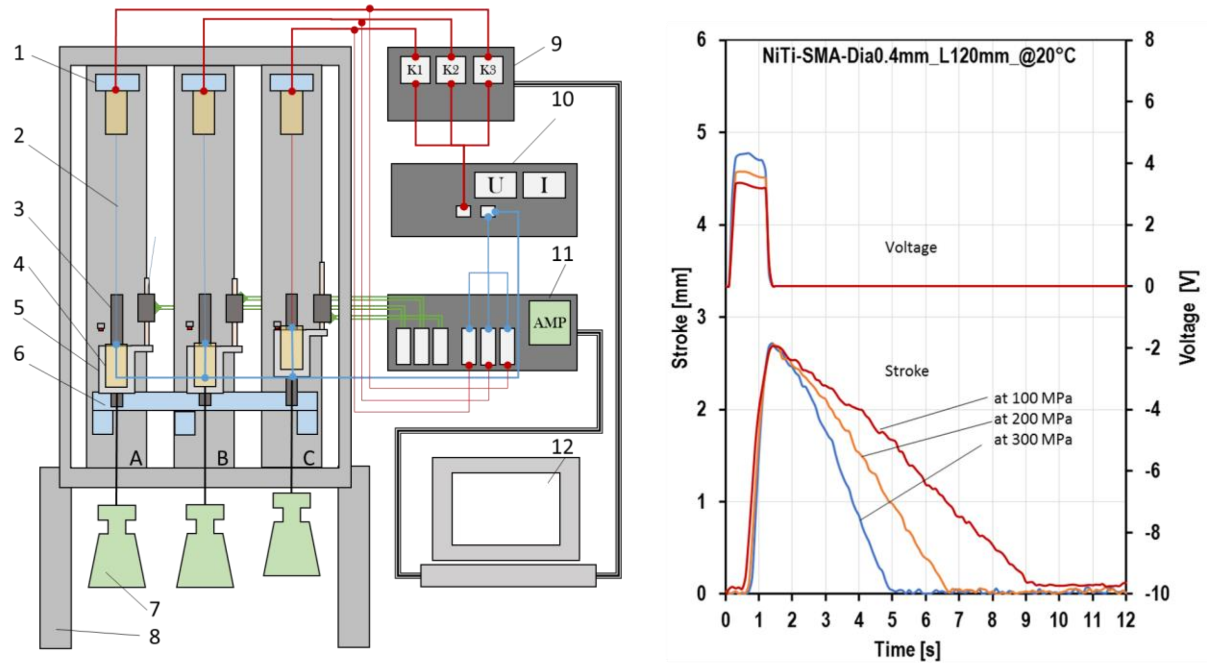
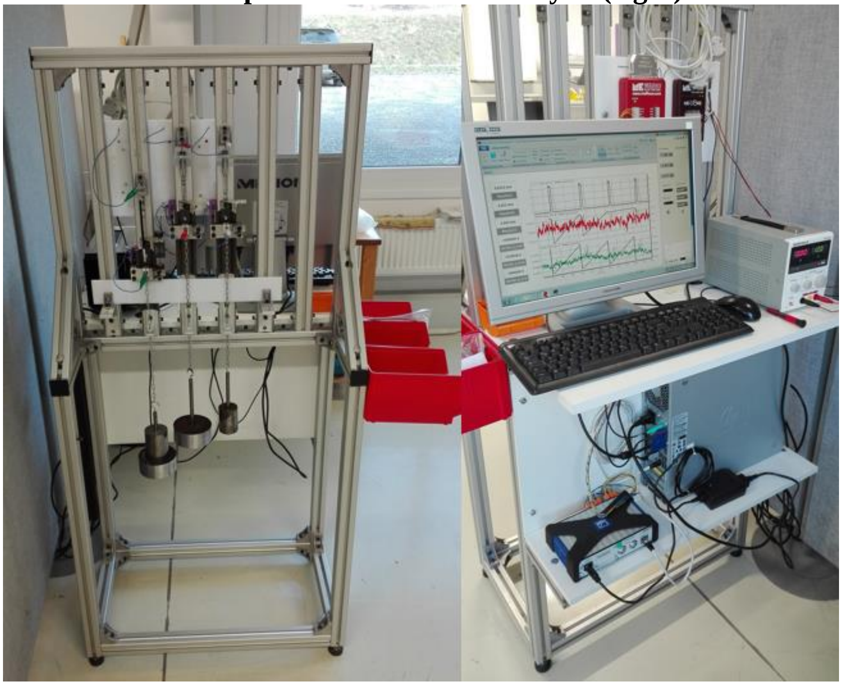


Figure 5 shows the real test rig in action. The time, electrical voltage and the stroke was recorded with 10Hz. The total measure involve 21.000 cycles. An influencing variable is the environmental temperature, which was eliminated by temperature control.

Figure 5: real test rig cycling several SMA wires at the same time with different loads (left) online process control and analysis (right)



4. DESIGN OF EXPERIMENTS

New products have to be developed with limited costs, in a short time and with high quality. Therefore, an optimal planning of the experiments that have to be performed is of great importance. The Design of Experiments (DoE) is a proven method in engineering as well as in the operational environment. It is, for example, used in process optimization, production and product development. [11]
The problems faced in those fields are usually in the form of comparisons among a set of influence factors in respect to some of their effects which are produced when they are applied to the experimental units. [12]
According to [13], DoE methods can be separated into *classical methods* and *modern methods*. While the classical methods require high mathematical and temporal expenditure due to necessary testing of all influence factors, modern methods (as developed by *Shainin* and *Taguchi*) allow faster and more efficient testing of products or processes.

DoE means detailed planning of experiments, with systematically assigned influence factors. Those influence factors are then specifically adjusted in order to reach pre-defined quality features or to optimize the product/process. [13]

The classical methods often have a straightforward approach to determine the influence of the different factors as well as the correlation between them. Here, one can take the full factorial design as an example, where every possible combination of the influence factors in different settings is tested.
If a linear influence of a factor is given, it is sufficient to allow only two settings of that factor in the tests. In the other case, at least 3 different settings of the factor have to be tested.

In example shown in table 1, three influence factors with linear influence are tested with full factorial manner. The numbers on the left side denote the number of the test runs. A, B and C denote an influence factor. The minus sign denotes that the factor is on the lowest setting in that test, a plus sign denotes the highest setting. For example, in the third test the factors A and C are set to the lowest setting, while B is on the highest setting. [Table cf. [13]]

Table 1: Fullfactorial Design of Experiments cf. [13]

	A	B	C
1	-	-	-
2	-	-	+
3	-	+	-
4	-	+	+
5	+	-	-
6	+	-	+
7	+	+	-
8	+	+	+

It is obvious that in the full factorial design the number of tests n_t grows exponentially with the number of tested influence factors n_f. We have

$$n_t = 2^{n_f} \tag{1}$$

If all influence factors have a linear influence, and

$$n_t = \prod_{i=2}^{\infty} i^{n_i} \tag{2}$$

If there are influence factors that have to be tested in more than one setting, where n_i is the number of factors that have to be tested in *i* different settings.
For example, if there are two factors which have to be tested in five different settings and four factors which have to be tested in three different settings we get a total number of:

$$n_t = 5^2 * 3^4 = 2025 \tag{3}$$

Necessary tests. Note that the numbers are fully artificial and serve only the understanding of the example.

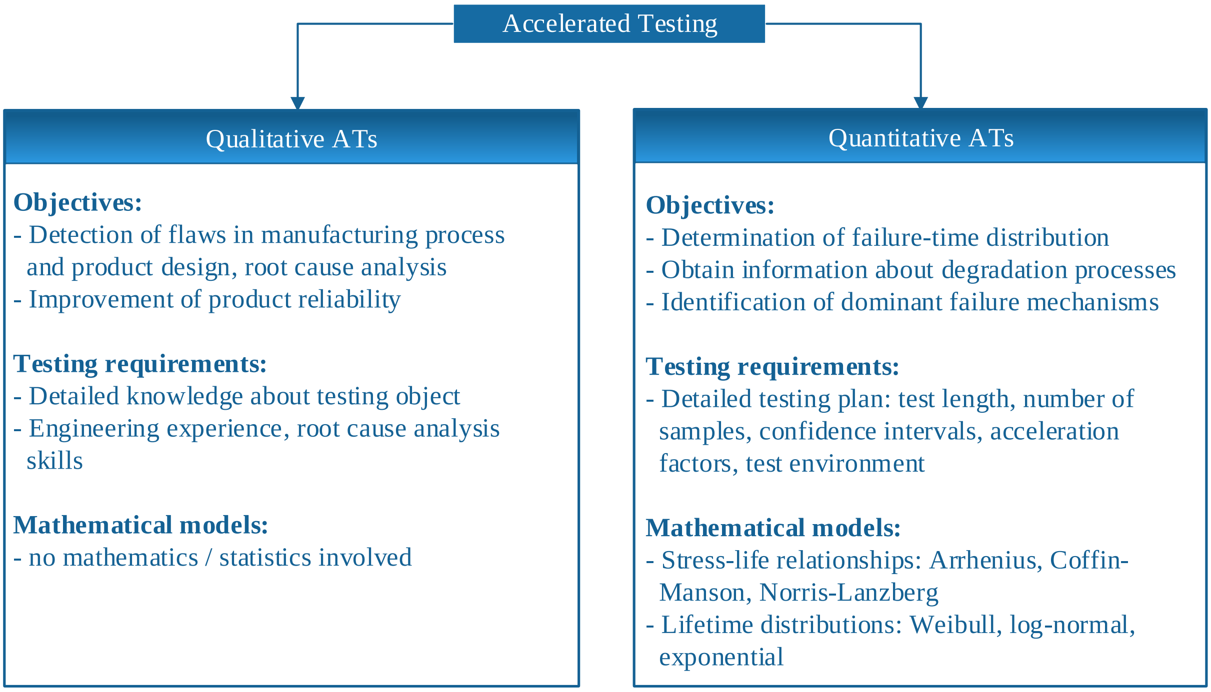
The full factorial design enables the engineer to determine the influences of the different factors as well as their correlation. However, since the number of needed tests grows exponentially, it is not recommended to use this design with a large number of factors and/or a large number of factor settings that have to be tested for a single factor.

In modern methods, the number of necessary tests can be reduced significantly by using pretests or by the usage of the experience and knowledge of experts that are familiar with the tested products or processes. By that, the number of influence factors is reduced to a smaller amount of important factors. For further information on the classical methods as well as the modern methods refer to [13].
In general, DoE enables its users to understand the influences of different factors as well as their correlation to each other. It is, however, necessary to meet certain conditions and to provide the required foundation. For further information on the required conditions as well as a detailed presentation of what can happen if those conditions are not met refer to [11].

4. ANALYSIS OF TESTING RESULTS

According to [14], “Accelerated tests” (ATs) is a term used for two completely different kinds of tests with different purposes, “qualitative ATs” and “quantitative ATs”. The key differences are presented briefly in figure 6 (for further information regarding accelerated testing refer to [15]).

Figure 6: Accelerated testing methods



Qualitative ATs are used to identify product weaknesses caused by flaws in the product´s design or manufacturing process. It is done by increase of the stresses until the product fails. The aim is to improve the product reliability in a very short period of time, usually hours or days. These tests are performed on entire systems but can be performed on individual assemblies as well. Common names for this type of tests are HALT (Highly Accelerated Life Test), STRIFE (Stress-Life) and EST (Environmental Stress Testing) [16]. Tests of this type do not involve any statistical or mathematical methods. They are only used to make the product more robust, not to gain any knowledge about the product lifetime or the degradation process over time.

Quantitative ATs are used to obtain information about the failure-time distribution and degradation in a relatively short period of time (usually weeks or months) by accelerating the use environment. In most cases, a model to describe the relationship between failure mechanism and accelerating variables already exists. They are also well-suited for finding dominant failure mechanisms and are usually performed on individual assemblies rather than full systems. In order to set up a quantitative AT, several different parameters must be known, for example test duration, number of samples, desired confidence intervals, field and test environment, stress-life relationship and distribution model. It is of note that this kind of test is of interest for the purpose of the present study. The main focus of the testing phase is the calculation of the degradation as well as early prognosis of passing the test.

4.1 Acceleration models

One key factor is to determine the acceleration factor. It can be obtained by two different methods, either by using existing physical / chemical acceleration models or by determining empirical acceleration models by experimentation.

Physical / chemical acceleration models

Various physical / chemical models for well-understood failure mechanisms are already available. They describe the failure-causing process and allow extrapolation to use conditions for specific environment variables. The relationship between accelerating variables and the actual failure mechanism is usually extremely complicated. However simple models which adequately describe the process already exist. Examples for some acceleration models can be found in [14].

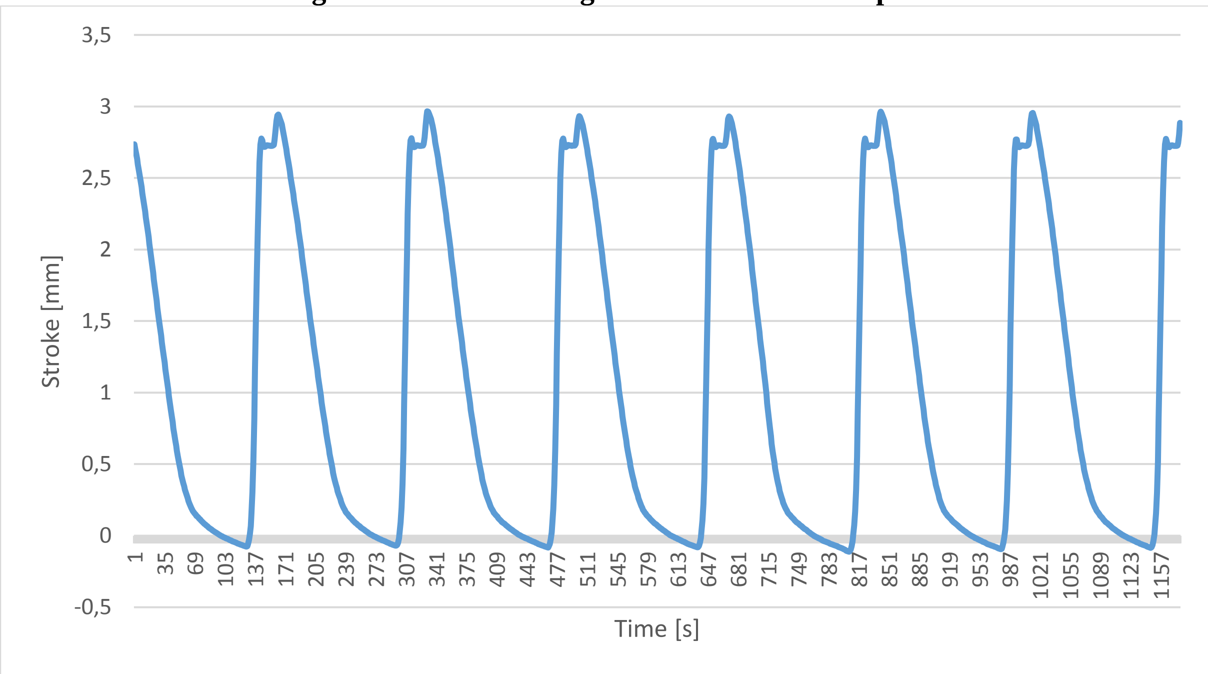
Empirical acceleration models

If there are no chemical / physical models to describe the failure-causing processes adequately it may be necessary to develop an own empirical model by experimentation. An empirical model usually provides an excellent fit to the available data. Extensive empirical research regarding possible failure mechanisms and different stress variable combinations is needed to justify the needed extrapolation. For the reason that there are no existing acceleration models for smart materials, a further purpose of the study is to develop an empirical model based on the testing results.

4.2. Acceleration methods

Increasing the usage rate: Products that are not in continuous use, can be accelerated by increasing the usage rate. This means that the time between the load phases is reduced. It has to be considered whether the increased use rate changes the cycles to failure distribution. This kind of acceleration is already performed within this study. The times between the load phases, which may take minutes to hours in the automotive industry are reduced to zero during the testing. An example of the data record performed on the existing test rig is presented in figure 7.

Figure 7: Increased usage rate based on stroke plot



Obviously, the presented example shows only several cycles within 1200 seconds out of an entire test which is considered for 300.000 cycles. Nonetheless, the entire test is recorded in the exactly same manner.

The complete record of the trial test is shown in figure 8. It is established based on the plot of a maximum stroke belonging to each cycle. Here, all in all 89 cycles are shown which is obviously much less than the record of an entire test and therefore shall be treated artificially. Based on the propagation of the maxima, some statistical test may be applied for the analysis of the test. For example, in the red sectors a trend analysis (e.g. regression analysis or linear trend estimation [17]) can be performed in order to examine the degradation in these areas. Furthermore, the examination of the change of a certain levels (highlighted by the green areas) of maxima can be performed based on significance tests. For the comparison of samples, different significance tests are available. In this case, nonparametric tests can be applied since it is not verified if the samples are normally distributed.

The null (and alternative) hypothesis of Mann-Whitney U test [17]

$$H_0 : F(z) = G(z) \ (and \ H_1 : F(z) \neq G(z - \theta) \ ) \tag{4}$$

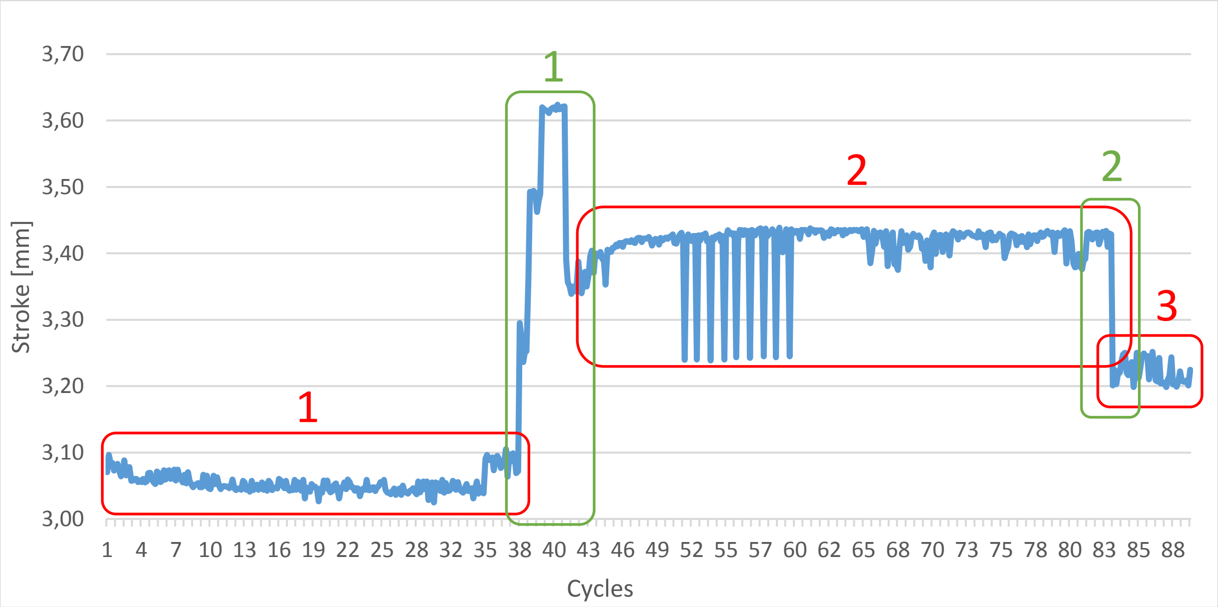
that the samples have the same focus and the null (and alternative) hypothesis of Levene's test [17]

$$H_0 : F(z) = G(z) \ (and \ H_1 : F(z) \neq G(\theta z) \ ) \tag{5}$$

that the variances of the samples are equal are described based on formulas 4 and 5 respectively.

There is a wide range of further analysis possibilities. Though, all of them will be considered in the future work depending on the results gathered out of long term tests.

Figure 8: Complete record of the trial test



Increasing the aging-rate: By increasing experimental variables like temperature, humidity or radiation, chemical processes that lead to certain failure modes can be accelerated. Here, the application of various ambient temperatures is planned in the future. For this purpose, a new test rig similar to the one presented in figure 5 put in a climate chamber is designed and will be build up and used in the further studies. Based on the results, the influence of the temperature will be considered as a further variable for the acceleration of the tests.

Increasing the level of stress: If the environmental stress exceeds the strength of the testing object, the unit (prototype) will fail. This means that a unit operating at higher stress levels will generally fail after a shorter space of time than a unit at lower stress levels (e.g., amplitude in temperature cycling, voltage, or pressure).

4. SUMMARY AND OUTLOOK

This paper presents a concept for a test rig as well as the statistical set up of experiments for the purpose of testing of shape memory alloys. For this purpose, fundamentals of shape memory alloy actuators are discussed briefly for the overall understanding of the purpose of the study. Furthermore, a concept for the experimental setup for testing of smart materials including some considerations of further development are discussed in detail. For the setup of the experiments, some method out of the design of experiments field are presented and discussed regarding their advantages and disadvantages. Finally, some statistical methods for the analysis of the results of accelerated testing are proposed regarding the proper applicability. Here, also the accelerated testing in discussed based on the purpose of this study.

In the future work, real data gathered from the long time experiments will be analyzed. Based on this analysis, acceleration factors shall be calculated depending on various parameters. Finally, a prognosis method shall be established in order to define already during the test if the tested actuator is going to pass the test or not.

The final result of this study shall be a guideline consisting of the description of the test rig, design and setup of the test, analysis method as well as the prognosis algorithm for smart memory alloy actuators being under development. Based on the proposed guideline, testing of SMA actuators shall be harmonized.

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