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Long-time stability of shape memory actuators for pedestrian safety system

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Materials

ABSTRACT

Purpose: Pedestrian safety systems play an increasing significant role to reduce injuries and fatal casualties caused by accidents. One automotive safety system for pedestrian protection is the bonnet lifting system. Using shape memory alloys (SMA) the existing systems could be simplified, performing the same function through new mechanisms with reduced size, weight and costs. A drawback for the use of SMA in such safety systems is the lack of material knowledge concerning the durability of the switching function. This paper gives an introduction to existing bonnet lifting systems for pedestrian protection, describes the use of quick changing SM actuators and presents the testing facilities and some results of the study concerning the long-time stability of the tested NiTi-wires.

Design/methodology/approach: A large number of NiTi-wires was trained, exposed up to four years at elevated temperatures and tested regarding their phase change temperatures, times and strokes.

Findings: It was found out that A_p-temperature is shifted towards higher temperatures with longer exposing periods and higher temperatures. However, in the functional testing plant a delay in the switching time could not be detected.

Research limitations/implications: For future works it is suggested that more NiTi-specimens at longer ageing periods should be tested, stress should also be applied by a constant load and the functional testing plant should be further optimized.

Practical implications: It can be concluded, that the use of quick changing SM actuators in safety systems could simplify the mechanism, reduce maintenance and manufacture cost and should be insertable also for other automotive applications.

Originality/value: This paper gives some answers concerning the long-time stability of NiTi-wires that were missing till now. With this knowledge the number of future automotive applications using SMA can be increased.

Keywords: Smart materials; SMA; Pedestrian safety system; Actuators

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1. Introduction

Recently the number of safety systems in modern cars has been increased steadily and thereby caused a reduction of injured or killed car passengers worldwide, in spite of the fact that the total car number increased from year to year [1-4]. In contradiction to the elevated security for car passengers the number of pedestrians that were slightly, severely or fatally injured during car accidents is still very high; see Figure 1 [5]. One effective automotive safety system for pedestrian protection is the bonnet lifting system [6]. In the past years different researchers have presented such systems [7,8] that generally are able to lift the bonnet during a crash with a pedestrian in order to absorb a part of impact energy when the pedestrian crashes into the bonnet and thereby reduce pedestrian's injuries. Besides the above mentioned systems that are not yet ready to market, some systems have been used in a series of cars, such as Honda Legend [9], Jaguar SX [10] and Citroën C6 [11] as shown in Figure 2.

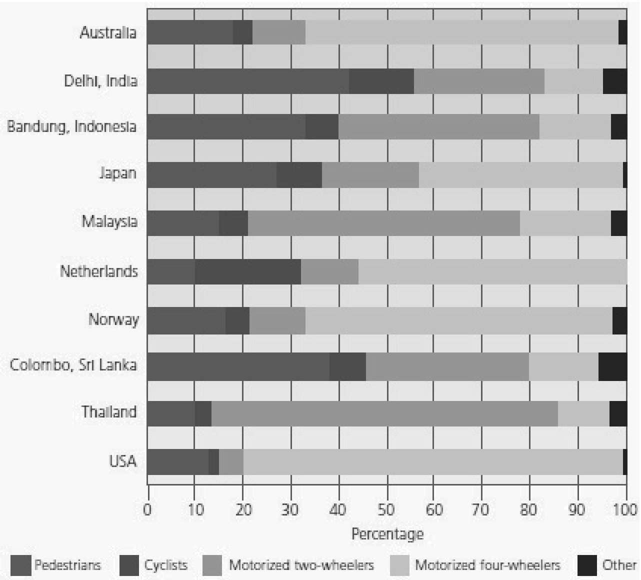

Fig. 1. Road users killed in various modes of transport as a proportion of all road traffic deaths [5]

However, for the lifting of the bonnet, fast actuators are necessary because there is only a very short reaction time - about less than 60 ms - from the initial touch of the pedestrian with the bumper to the crash of him into the bonnet. In all these existing systems the actuator operations are irreversible.

Our research group starts in 2001 to develop quick changing shape memory actuators in a phase, when the existing sensors in the bumper were not reliable enough to distinguish, whether a pedestrian's leg, a ball, a bird or something else was touched and therefore had the disadvantage of being very cost intensive because the pedestrian safety system has to be renewed after every faulty activation. Therefore our idea is to replace the used electrical, pneumatic or hydraulic actuators by reversible shape memory actuators.

Fig. 2. Pop-up bonnet technology in Citroën C6 [11]

2. Bonnet lifting system, introduction to shape memory alloys and their function in the pedestrian safety system

2.1. Description of the existing bonnet lifting system

A pedestrian protection system was developed by the consortium IPPS, Intelligent Pedestrian Protection Systems [12]. In this safety concept the companies co-operate since 2001. The concept of these companies contains a give-way bumper, fiber-optical sensors and an active hood, raised by a pneumatic muscle – instead of pyrotechnical actuation. The result is a drivable prototype in which the companies combined their know-how. To decrease the risk of leg injury, a design was developed with a soft foam that is situated between bumper cover and bumper cross beam. In addition to this, new sensors were also integrated into the bumper. The functional principle of these fiber-optical contact sensors acts in different stages. In parts the plastic sheath of the light wave conductor is removed. If the fibers are bent, a part of the light there reflects from the fiber. This reflection is depending on the bending intensity and therefore the light loss registers how strong the fiber has been bent. By laying several preserved fibers horizontally above the bumper and removing different segments of the sheath, a distortion picture of the vehicle front arises. Through this the control module can recognize if a pedestrian is going to crash into the bumper. Then it sends an impulse for lifting the modified bonnet to catch pedestrian's head softly [13].

In this system a pneumatic muscle was activated for lifting the bonnet. It consists of a tube with varying layers of elastomer in combination with thread meshes. If the quick switching valve opens, compressed air flows into the tube. It becomes thicker and contracts lengthwise. In combination with a reversing mechanism it raises the bonnet. In the prototype of IPPS the control unit signals at the latest 15 milliseconds after the first contact on the release. Within further 35 milliseconds the bonnet is raised some centimeters. To operate fast enough, the muscle needs compressed air from cartridges or a type of storage that is filled by a compressor. This system weights less than 1kg for sensor, control device and pneumatic actuator, but its drawback is the weight of the compressor. The system is schematically shown in Figure 3.

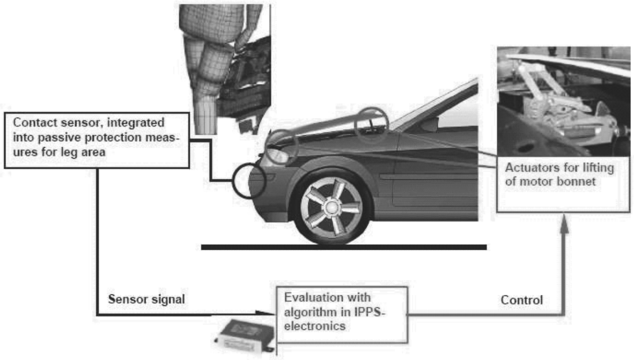

Fig. 3. System set up [13]

In order to profit of the advantages of this system but to avoid its disadvantages this active bonnet system was chosen as an outstanding example for quick changing shape memory actuators. The replacement of the described pneumatic muscle through shape memory actuators leads to some additional advantages, e.g. reversible function, compact construction, and a less-cost-intensive-solution. The requirements for any actuator used in automotive vehicles are strongly dependent on the position where the actuator is placed. In the case of the IPPS system the requirements for the SM actuator were specified as follows [14]:

- Operating temperature: -40 to +125°C
- Actuating time: < 35ms
- Actuation force (using a ratio): 200 to 300N
- Long-time stability of the used materials

2.2. Introduction to shape memory alloys

Shape memory materials show the particular capacity to revert to their original form when heating if they are plastically deformed below a critical temperature before [15]. This exceeding effect is the result of a solid state phase change of these special alloys (SMA). Figure 4 shows this mechanism that is named martensitic phase change.

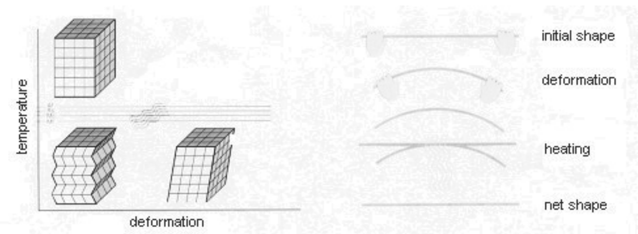

Fig. 4. Martensitic phase change and shape memory [16]

The high-temperature modification of the lattice (austenite) "flips over" into a twinned martensite structure (from top left to bottom). This martensite lattice can be de-twinned up to 8% (for NiTi). As long as the material remains below the phase change temperature, this deformation is lasting. Heating of the deformed martensite above the phase change temperature causes the reversion into the original space-lattice structure and therefore into the original shape of the material. This behaviour is the basis of the shape memory effect.

Generally the shape memory effect involves a considerable reset force and therefore facilitates their application as actuators. Therefore it is possible to create a spontaneous contraction of a metallic element in the range of some percent through heating. Such actuator applications can be found e.g. as adjusting, combining, supporting or contacting elements, as active implants or as high damping spring elements. They also find applications as sensors and actuators in passenger cars, as it is described in the next paragraph.

2.3. Shape memory alloys in the automotive industry

In a modern passenger car there are several electromagnetic actuators for different functions, including comfort systems for the driver and passengers, actuators for engine control or vehicle control, servo-microactuators for power systems and aerodynamics. New approaches based on smart materials, instead of the traditional electromagnetic motors, can simplify the actuation in most cases, performing the same function with reduced size, weight and cost, optimizing the movement and also offering the opportunity to implement new functions [15]. Some general potential vehicle applications for shape memory materials are shown in Figure 5.

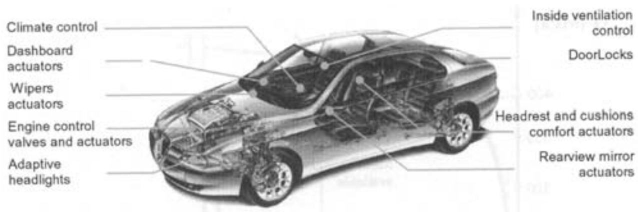

Fig. 5. Potential vehicle applications for shape memory components [15]

The use of shape memory actuators as an alternative to electromagnetic motors for automotive applications, particularly for comfort purposes, offer some main advantages, smooth direct movement with high torque or force, no additional mechanism, noiseless operation and intrinsic reliability, since the motion is related to the physical properties of the material. Therefore the most interesting actuation functions are those in components used occasionally with non rotary movements, such as rear-view mirror folding, movement of the climate control flaps for air flow adjustment and lock-latch controls [17].

On the other hand, the use of adaptive working safety systems for automotive applications is continuously increasing. In modern automotive engineering, especially quick changing actuators are used in applications concerning safety regulations. Nowadays the actuators are mainly operated by complicated mechanical systems, very often by so-called pyrotechnic ignition devices. By using intelligent materials, e.g. SMA, an actuator function can be realized easily. Additionally, in comparison with systems driven by pyrotechnic ignition devices, with such systems it is possible to carry out the actuator function repeatedly, or also reversibly. But the use of shape memory materials in such safety systems is reduced because of the lack of material knowledge on this section. A central problem is the durability of the switching function (long-time stability of the shape memory effect), which still has to be proved.

2.4. Quick changing shape memory alloys

An easily and quickly working actuator principle based upon NiTi wires for a future use in a bonnet lifting system for pedestrian protection was developed in different steps [18,19]. In these works it has been proved, that SMA are suitable to fulfill the requested actuating times and forces for this application [18]. Before the paper will focus on the long-time stability of these working elements, some results and the used material specification are given.

In various test series NiTi wires with different diameters were tested to achieve the short contraction times and to lift the corresponding mass of a bonnet of 20 kg. The activation of the shape memory elements was realized by electrical discharge of a capacitor system. Best results were achieved using a configuration with 30 NiTi wires that were plaited to a so-called shape memory muscle. This configuration was actuated via electrical discharge of a capacitor and was able to lift a weight of 20 kg (bonnet) over a lifting distance (stroke) of 12.5 mm within less than 35 ms. Figure 6 shows the testing plant and in Figure 7 the stroke vs. time diagram is given.

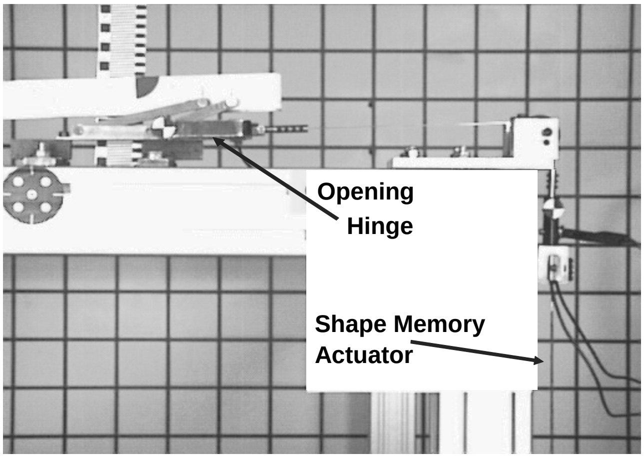

Fig. 6. View of the actuator testing plant [16]

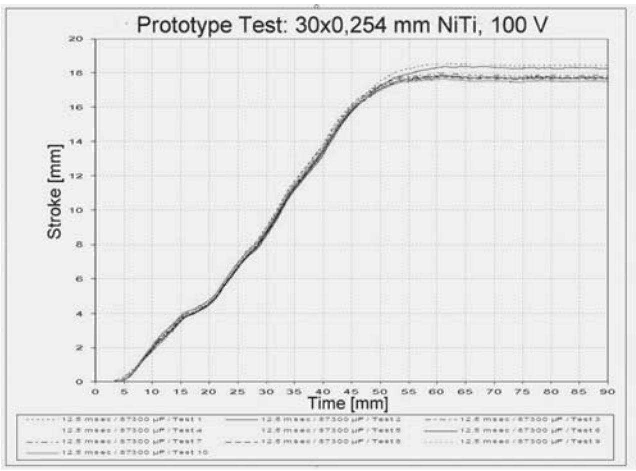

Fig. 7. Stroke vs. time diagram of the SM actuator

One single shape memory wire has a diameter of 0.254 mm and the following supplier specification "[Memory-Metalle GmbH, data sheet]": NiTi alloy Dy90, high temperature actuator alloy with A_P 95°C. For having the same starting material for the long-time stability tests and to achieve reproducible results the wires were trained under a loading that corresponded to 135 N/mm^2. The wires were trained 80 times by electrical actuation in special devices that allow fixing and training of 90 wires at the same time. After the last training cycle the shape memory wires were fixed in the pre-strained condition, in other words under the tension of the 135 N/mm^2, to simulate exactly the mounting condition of the quick changing actuator in the car.

3. Ageing of the wires and test facilities

The long-time stability of the shape memory actuators is a significant point that has to be assured. Safety systems in general could be activated within the first days of a car's lifetime or after several years, but the functionality of the whole system and especially the actuators should be reliable at any time. In practice the long-time stability can be proved through a testing method upon exposed specimens. By exposing the shape memory specimens a so-called ageing process occurs and a statement concerning the functionality of the specimens can be made. The test procedure bases on the well known fact, that the parameters time and temperature have a direct interrelationship. So it is possible to achieve artificial ageing when the factor time is replaced through the factor temperature in a certain range. In the case of SMA this interrelation cannot completely be used because no phase change should occur during ageing. To assure at every temperature that the pre-strained wires still have martensitic structure, according to the requirements for parts in the engine compartment, the ageing temperatures are chosen between 60 and 140°C. In checking tests it was certificated with increased weights that even at 140°C the pre-strained wires were still martensitic in the fixing device. For each test step concerning ageing temperature and exposure time six specimens were aged over different periods of time up to 1560 days. Figure 8 gives an overview of the temperature groups and the planned exposure time in the ageing matrix.

According to the experiences in ageing tests of metallic material without shape memory effect, possible ageing effects are expected after a short time in the high temperature groups and in a longer time in the lower temperature groups, respectively. Therefore the removal of specimens aged at 140°C and 120°C started already some days after the beginning of the ageing, while the specimens aged at lower temperatures are planned to be removed after a certain time, see Figure 8. At the beginning of the ageing procedure more wires were exposed in the ageing furnaces, so that it was also possible to realize the tests of the pointed boxes. It also has to be noticed, that there is a big gap between the removal after 180 days and 1560 days. This fact was not planned at the beginning of the ageing process, but results from the test data and the idea to realize the longest possible exposure time with the last batch of specimens.

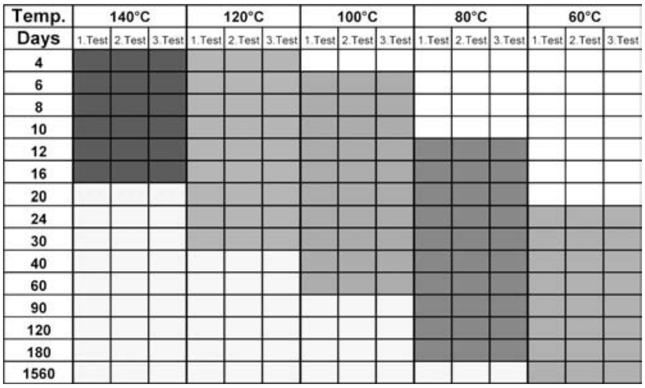

Fig. 8. Ageing matrix

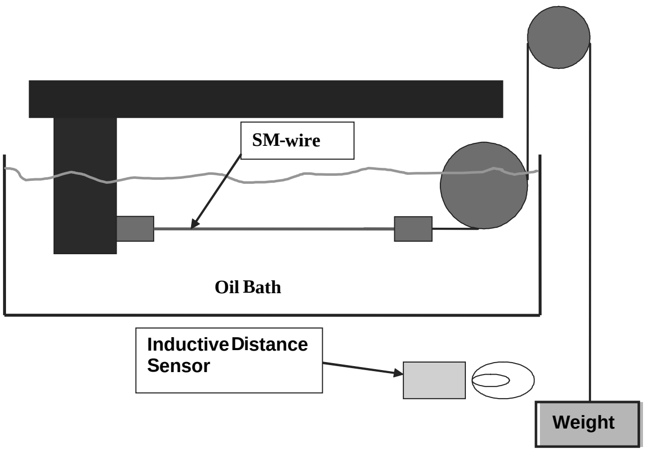

Fig. 9. Oil bath testing facility, schematic view

In two special developed testing facilities these specimens were further examined. The first facility is schematically shown in Figure 9. Up to six specimens of the shape memory wires can be horizontally fixed on the one side. The other side of each specimen is connected over two pulleys to the weight that causes a specified tension of 135 N/mm^2 in the shape memory wire. By heating and cooling the oil bath the specimens are cycled and through inductive distance sensors the exact length of each specimen is measured and plotted in a temperature-length diagram. By means of graphical evaluation the characteristic points of the phase changes, such as A_s, A_f, M_s, M_f, can be determined.

With the data of the phase change temperatures and the contraction values even the smallest behavior differences can be analyzed in the specimens. By comparing the data of the stored and aged specimens with a reference wire (kept at room temperature), possible ageing effects upon the shape memory effect can be noticed immediately. If no differences in the wire behavior are observed between the reference wire and aged wires at different temperatures and durations, the shape memory effect of the actuator wires is probably not impaired.

A second testing machine was designed in order to investigate a possible influence of ageing upon the shape memory effect of actuator wires concerning their functionality.

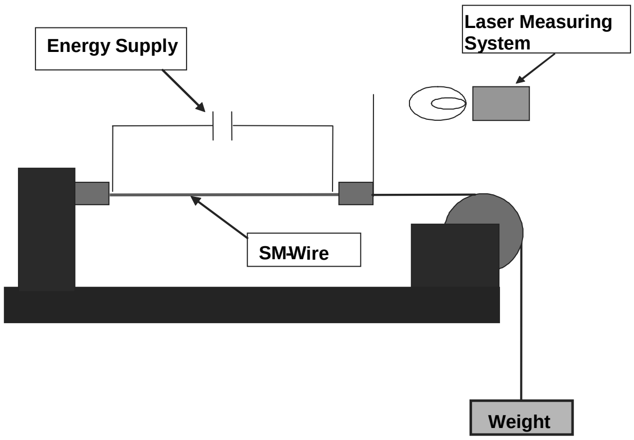

Fig. 10. Quick changing testing facility, schematic view

As shown in Figure 10 a single shape memory wire specimen is connected on one side to a fixed mounting and on the other side to a mobile weight over a pulley. When the wire is heated quickly by electrical discharging the phase changing from martensite to austenite takes place. The hereby caused wire contraction and the activation time are measured by the laser sensor. In order to achieve short contraction time and therefore a fast activation, small wire diameters are used in combination with high electrical power density.

4. Results and discussion

4.1. Oil bath tests

A typical diagram of the results achieved in the oil bath tests is shown in Figure 11. In this diagram NiTi SM wires with diameters of 0.254 mm and lengths of 244 mm, aged at 120°C for 4 days were examined. Each specimen was cycled three times between 10 and 170°C and compared with a reference wire.

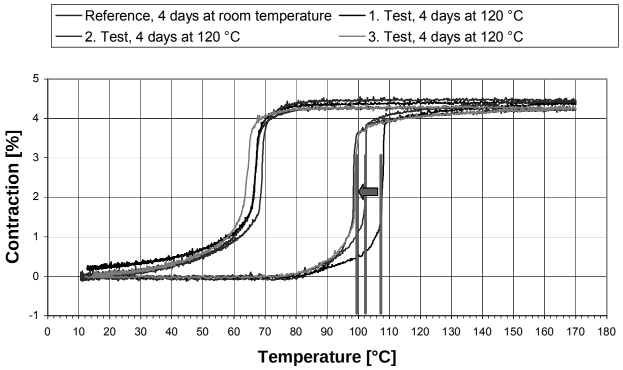

Fig. 11. Oil bath results: Contraction-Temperature diagram of specimens aged at 120°C for 4 days, three tests

All four graphs (each one as average graph of three specimens) show the same contraction values between 4.2 and 4.4%. The red lines in the diagram indicate the A_p-value of each graph. A_p is the characteristic value 'austenite peak' that indicates the temperature point, where the austenite phase transformation has its highest speed. A difference can be observed in the A_p-temperatures of the four graphs: Compared to the reference wire, the phase changing temperature at the first test after ageing is slightly higher. In the second and third test of the same wire the observed displacement was set back almost to the A_p-temperature of the reference wire. This elevation can be explained with the 'effect of the first phase change transformation'. This well known effect means, that during the first phase change transformation the values concerning phase change temperature and also phase change size (contraction) are slightly higher because of the ageing. This behavior is due to a natural ageing of stored shape memory material and also takes place with the artificial aged shape memory specimens of this investigation.

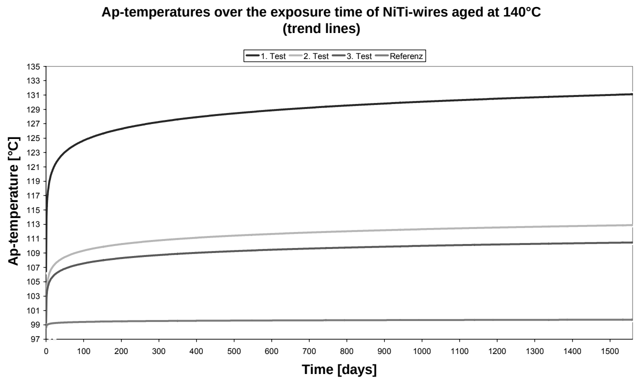

Fig. 12. Global map of the NiTi-wires aged at 140°C for ageing times ranging from 1 hour to 1.560 days

According to this test method three wires of every temperature group and planned exposure time (shown in the ageing matrix in Figure 8) were tested. Then for each temperature group an 'overall diagrams' that we call 'global map' was prepared where possible shifting of the A_P-temperatures can be seen as trend lines over the exposing time till 1.560 days. In Figure 12 the data for the temperature group aged at the highest exposing temperature of 140°C is given.

It can clearly be seen that the A_P-temperature of the first test is shifted to higher values. In comparison to the reference data the shifting is about 20 K within the first days and nearly 32 K at 1560 days. The trend lines of the second and third test have the same course but their displacement concerning the reference line is much smaller. All the trend lines – even the reference line – are slightly rising with longer exposure time. It can be concluded that temperature has an immediate effect on the shifting of the A_P-temperature, especially in the first test after ageing. The influence of the exposure time is less intensive but also leads to higher A_P-temperatures.

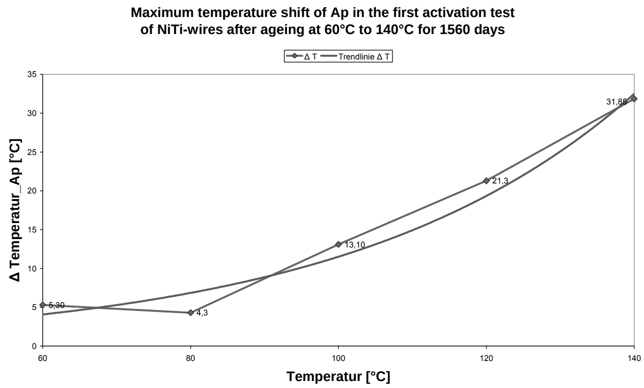

Fig. 13. Maximum shifting of A_P-Temperature of the aged wires at different temperatures for 1560 days

In the other temperature groups the same observations were made. Depending on the fact that the maximum shifting of the A_P-temperature occurred always in the first test, in the following data only the trend lines of the first test were analyzed. It was observed that the shifting value of the A_P-temperatures is less intensive with lower ageing temperature. The shifting of the A_P-temperatures of the first tests over the ageing temperature is shown in Figure 13.

4.2. Conclusion concerning the results of the oil bath tests

Concerning the results of the oil bath tests it can be stated, that ageing temperature and exposure time have a measurable effect upon the tested shape memory wires. Higher ageing temperatures lead to stronger shifting of the A_P-values while the influence of longer exposure time is not so strong. The displacements have their maximum in the first tests after ageing, while the second and third test lead to smaller shifting. The shifting itself can be classified as relatively small but always leads to higher A_P-values. But a final conclusion concerning the actuation of the trained and aged shape memory elements and thereby concerning the function of the bonnet lifting system cannot be done only with the test data of the oil bath tests.

4.3. Quick changing tests

In contradiction to the oil bath tests the quick changing tests could be carried out in a shorter time (about 30 minutes for one wire including set-up time). In this test procedure only two wires for each temperature-time group were tested and the average graph was compared to the reference graph. The third aged wire still serves for further investigations. In the quick changing tests the NiTi wires were electrical activated via discharge of a 47000 µF-/100 V capacitor that was loaded to a voltage of 30 V. The pulse time was fixed to 30 ms. To avoid a strong overshoot of the load because of the fast acceleration, the impulse was absorbed through a protector that was placed at a distance of 9 mm above the load. In the following Figure 14 it can be seen that the protector could not absorb the whole energy of this impulse: The weight was rejected, lifting value drops from 9 to 6 mm and swung to a value between 7 and 7.5 mm at 150 ms.

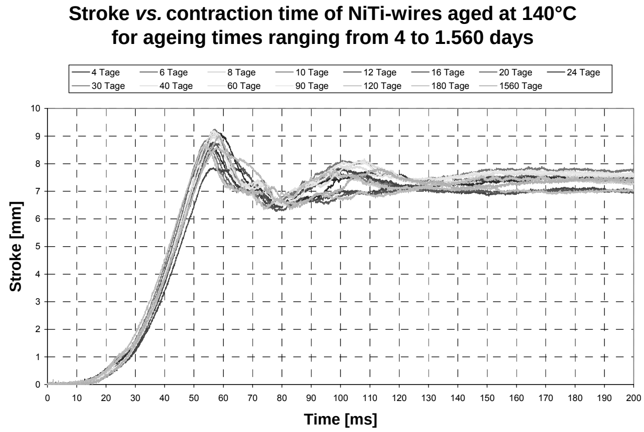

Fig. 14. Quick changing test results: Stroke-time diagram of NiTi-wires aged at 140°C for exposure times from 4 to 1.560 days

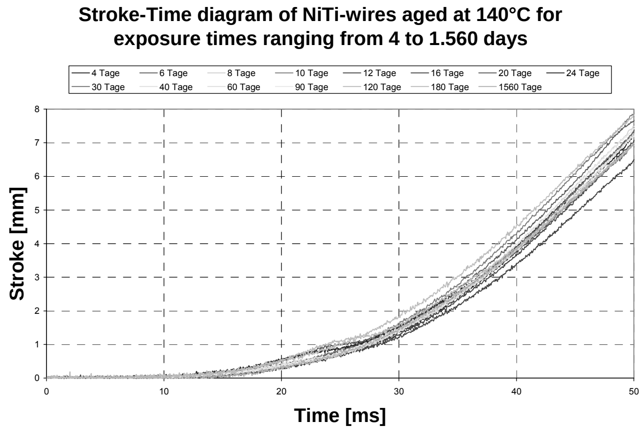

Fig. 15. Quick changing test results: Detail from the Figure 14

In all the test data of the different temperature-time groups no significant difference to the reference specimens could be observed. For knowing whether the little differences of the data are subjected to any systematic, the first 50 ms of the graphs in Figure 14 were observed in detail (Fig. 15). In 50 ms the actuator wire contracts 6 mm and this would probably be the working range in the bonnet lifting system. Even this closer analyze did not show any systematic distribution of the results. It can be stated that the small differences were not caused in the material of ageing differences, but in the accuracy of measurement.

4.4. Conclusion concerning the results of the oil bath tests

By the results of the quick changing tests it can be stated, that ageing temperature as well as exposure time has no measurable effect upon the function of the tested SM wires. First these results seem to be a contrast to the results of the oil bath tests, where a slight shifting of the A_P-temperatures towards higher values was observed and therefore the activation with the same constant energy logically should lead to a measurable slowing-down of the contraction time.

Considering the results of both tests it can be concluded, that through the high-speed discharge of the capacitor such a high energy is applied upon the shape memory wires, that even for a A_P-temperatures raise of about 32 K (in the case of the ageing at 140°C for 1560 days) no measurable influence can be detected concerning the function of the actuator wires.

5. Conclusions

In automotive applications, especially in safety systems, a lot of electromagnetically driven actuators are integrated to run comfort and control these systems of modern passenger cars. Using shape memory alloys these existing systems can be simplified in most cases, performing the same function through new mechanisms with reduced size, weight and costs. But the use of shape memory materials in such safety systems is reduced because of the lack of material knowledge on this section. A central problem is the durability of the switching function (long-time stability of the shape memory effect), which still has to be proved.

This paper gives an introduction to some bonnet lifting systems for pedestrian protection and describes the use of quick changing SM actuators applied on prototypes. Furthermore the testing facilities and some results of the study concerning the long-time stability of the tested NiTi-wires are presented and discussed.

The used material specimens were trained and thermo-mechanically aged under constant stress at elevated temperatures during different time periods. In the testing plants they were investigated concerning their switching temperatures A_p, contraction times and strokes.

Concerning the present results it can be concluded:

1) Pedestrian safety systems play an increasing significant role to reduce injuries and fatal casualties caused by accidents. The practice proved that the bonnet lifting system is an effective automotive safety system for pedestrian protection which has been adopted by more and more car manufactures.
2) The results of prototype tests proved that SMAs are suitable to fulfill the requested actuating functions in the bonnet lifting

system. The activation of the actuator element - 30 NiTi wires with a diameter of 0.254 mm that were plaited to a so-called shape memory muscle - was realized by electrical discharge of a capacitor system and was able to lift a weight of 20 kg (bonnet) over a lifting distance (stroke) of 12.5 mm within less than 35 ms.

3) The results of the oil bath tests proved, that ageing temperature and exposure time have a measurable effect upon the tested shape memory wires. Higher ageing temperatures lead to stronger shifting of the AP-values while the influence of longer exposure time is not so strong. The displacements have their maximum in the first tests after ageing, while the second and third test lead to smaller shifting. A maximum elevation of the Ap-temperature of 32 K was measured in the specimens aged at 140°C for 1.560 days.
4) By the results of the quick changing tests it can be stated, that ageing temperature as well as exposure time has no measurable effect upon the function of the tested SM wires. First these results seem to be a contrast to the results of the oil bath tests, where a slight shifting of the AP-temperatures towards higher values was observed and therefore the activation with the same constant energy logically should lead to a measurable slowing-down of the contraction time. Considering the results of both tests it can be concluded, that through the high-speed discharge of the capacitor such a high energy is applied upon the shape memory wires, that even for a A_P-temperatures raise of about 32 K (in the case of the ageing at 140°C for 1560 days) no measurable influence can be detected concerning the function of the actuator wires.
5) The use of quick changing shape memory elements as actuators in safety systems should be possible not only for the bonnet lifting system, but also for other automotive applications, compared with traditional complex and irreversible operation actuators.

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