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Intelligent materials in modern production – Current trends for thermal shape memory alloys

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Abstract

Thermal shape memory alloys show extraordinary material properties and can be used as actuators, dampers and sensors. Since their discovery in the middle of the last century they have been investigated and further developed. The majority of the industrial applications with the highest material sales can still be found in the medical industry, where they are used due to their superelastic and thermal shape memory effect, e.g. as stents or as guidewires and tools in the minimal invasive surgery. Particularly in recent years, more and more applications have been developed for other industrial fields, e.g. for the household goods, civil engineering and automotive sector. In this context it is worth mentioning that for the latter sector, million seller series applications have found their way into some European automobile manufacturers. The German VDI guideline for shape memory alloys introduced in 2017 will give the material a further boost in application. Last but not least the new production technologies of additive manufacturing with metal laser sintering plants open up additional applications for these multifunctional materials. This paper gives an overview of the extraordinary material properties of shape memory components, shows examples of different applications and discusses European trends against the background of the most recent standard and new production technologies.

Keywords: Thermal shape memory alloys; nitinol; additive manufacturing; metal laser sintering; selective laser melting

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1. Introduction

Besides the digitalization materials will play the role of a key technology in the 21st century. In this context a lot of research is being conducted on classical basic materials, like e.g. steel or concrete. At another level basic materials are going to be improved by applying special coatings or nanotechnological surface treatments on the one side or by creating very special multi material mixes on the other side, e.g. the addition of carbon fibers in order to create composite materials with very special properties. The highest class of modern materials is often referred to as "intelligent materials". Other frequently used terms for intelligent materials are functional materials or smart materials. According to the definition of Hornbogen and Mertmann [1] intelligent materials have the ability (a) to change strength or other structural properties when exposed to external stimuli, (b) to execute and control movements and (c) to generate a signal via a change in geometry or property by means of feedback.

In order to show these mentioned abilities intelligent materials can use different mechanisms. Ferromagnetic and ferroelectric materials for example are using the effect of the magnetostriction; the piezoelectric materials are using the effect of electrostriction. Finally, the mechanism of the shape memory alloys (SMAs) is based upon a crystallographic shear that can be released by magnetic field changes (magnetic shape memory materials, MSM materials) or temperature changes (thermal SMAs). This work focusses on the thermal SMAs and gives in the next paragraph first a short introduction of the shape memory effects and the extraordinary properties of these materials. In a following chapter some general applications are described to show their potentials in modern and future industrial systems. The main focus of this paper will be given in the last paragraph where the new production possibilities for the thermal SMAs by using additive manufacturing with metal laser sintering technologies are described and different standards and guidelines for thermal SMAs are generally discussed.

2. State of art concerning thermal shape memory alloys

Detailed information concerning SMAs can be found in a lot of publications. Out of this multitude the authors recommend [2, 3, 4, 5, 6, 7, 8, 9]. For showing their unique properties and their application potential a very short overview of the state of art will be given here. This knowledge is also necessary for a better understanding of the challenges of the new production technologies in the later part of this work.

2.1. Discovery of the shape memory effect

The shape memory effect (SME) first was discovered in 1932 in a cadmium-gold alloy [10] but the beginning of the investigations can be dated in the year 1962, when Buehler and Wang showed the SME in a nickel-titanium (NiTi) alloy at the Naval Ordnance Laboratory [11, 4]. Since then the trade name nitinol® is a synonym for the most commonly used group of SMAs that nowadays finds its technical application in many commercial fields, e.g. in medical industry, civil engineering and automotive industry.

A shape memory element is able to memorize and recover its original shape after it has been deformed by heating over its transformation temperature [12]. This unique effect of returning to an original geometry after an inelastic deformation is known as the shape memory effect (SME).

The SME occurs due to a temperature and stress dependent shift in the material's crystalline structure between two different phases, martensite (low temperature phase) and austenite (high temperature phase). The temperature, where the phase transformation occurs, is called transformation temperature or phase change temperature. The level of the phase change temperatures is mainly dependent on the chemical composition of the SMA and the thermomechanical training.

2.2. Characteristic values of thermal NiTi SMAs

Different values concerning the properties of thermal SMAs can be found in literature, depending on the company, institute and especially the year of the published data. In the last years a lot of investigation has been carried out to improve the quality of the SMA material and also to shift its limits. Table 1 presents some characteristic values of commercially available NiTi SMAs.

Table 1. Characteristic values of NiTi SMA. [15, 5/p.159, 3/p.9]

	NiTi	unit
One way shape memory effect (OWSME),max	8	%
Two way shape memory effect (TWSME),max	3,2	%
Phase change temperatures	-200 … +110	°C
Temperature hysteresis	30 … 80	K
Overheatable up to	400	°C
Thermal conductivity, martensite	9 … 10	W/mK
Thermal conductivity, austenite	18	W/mK
Linear thermal expansion coefficient,martensite	6,6	10^{-6} 1/K
Linear thermal expansion coefficient, austenite	11	10^{-6} 1/K
Specific electrical resistance	0,5 … 1,1	10^{-6} Ωm
Density	6,45	103 kg/m^3
Ultimate tensile strength, martensite	700 … 1100	N/mm^2
Ultimate tensile strength, austenite	800 … 1500	N/mm^2
Number of achievable thermal cycles	≥100 000	
Corrosion resistance	excellent	
Biocompatibility	excellent	

3. Applications

More than 20.000 worldwide patents have been issued on SMAs and their applications till 2014 [4/p.1080] and it can be concluded that for nearly all different technical areas SMAs can be used. A classification can be made according to the exhibited SME in each case (one-way SME, two-way SME, superelasticity), according to the functionality of the used shape memory element (free recovery, constrained recovery, work production or superelasticity) or finally by the application type of the shape memory element or shape memory system, respectively (actuator, sensor and damper). In this work a general overview will be given according to the respective industrial area.

3.1. Medical area

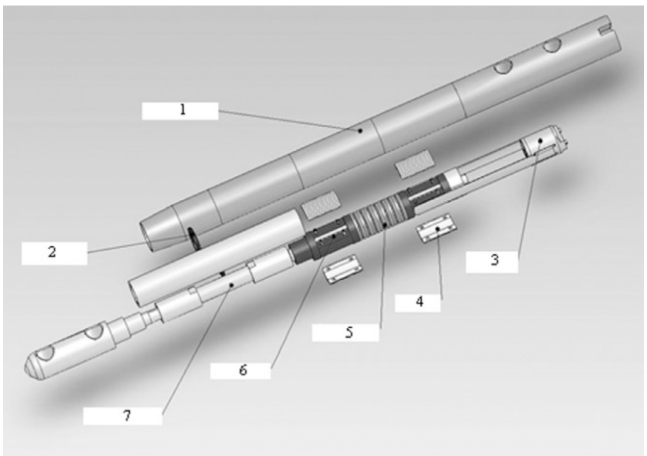

Fig. 1. The shape memory alloy limb lengthening (SMALL) nail. (1) external tube, (2) seals, (3) switch, (4) catches, (5) spring element, (6) thrust, (7) NiTi tube [20].

NiTi play a predestinated role in the medical field because of their excellent biocompatibility on the one side and their bone-like mechanical behavior on the other side. Therefore, it comes as no surprise that the first industrial applications in considerable quantities were bone clamps and stents. Even today, with stents the highest turnover in the field of the NiTi SMAs is achieved [16]. But using the SE of nitinol a high quantity of new applications was generated in the field of minimal invasive surgery, e.g. orthodontics, catch baskets for kidney stones or medical guidewires.

In this field our group at the HTWG and WITg is also developing a new medical device which is intended for bone elongation. The shape memory alloy limb lengthening nail SMALL® is using the thermal SME in combination with a bias-spring and a sawtooth profile and can be activated via high-frequency energy transport twice a day in order to create a bone lengthening of 1 mm per day.The procedure of bone extension and defect bridging using intramedullary nails is established [17, 18, 19] and shows some major advantages compared to external fixation devices, e.g. minimal risk of infection, better cosmetic results, more comfort for the patient and less hospitalization times. Furthermore, the new SMALL® will have some additional benefits like increased redundancy and permanent feedback signals regarding the current status of the extension. Fig. 1 gives an overview of this new system.

3.2. Civil engineering

SMAs can be easily used as dampers, both in the austenite and martensite phase. For SE-SMAs normally the austenite phase is present at room temperature. When such an element in full austenitic condition is loaded, the formation of the so-called stress-induced martensite takes place, see Fig. 1 loading and unloading of austenite. Hereby high elongations without plastic deformation of the material can be realized and, in other words, energy dissipation is executed through internally constrained phase changes.

Also in its martensite phase every shape memory element is able to dissipate energy during the pseudoplastic elongation on the martensite plateau. In this case energy dissipation is executed through deformation; see Fig. 1 the formation of de-twinned martensite by loading at low temperatures.

Most of all applications of shape memory elements in the field of damping are used to protect buildings against earthquakes. From 1995 to 1999, for example, within the framework of the European MANSIDE project, extensive work was carried out on the development of elements for earthquake protection of buildings using NiTi wires [21]. Since the components with the highest destruction potential during earthquakes are at very low frequencies, the elements used were loaded in cyclic tests up to a frequency of 4 Hz. In the simulation tests on vibrating tables, the hysteresis area was reduced with increasing frequency, but better results were achieved than with comparable rubber materials. When restoring the church in Assisi after an earthquake in 1999 SMAs were used [22]. Different devices with shape memory elements were used, whereby forces of up to 300 kN are specified per device with deflections of +/- 20 mm. In [23] are reported experiments upon plates of NiTi-SMAs that are tested as an intelligent damping element for bridge supports. Due to the austenitic phase transformation occurring between 19 °C and 32 °C, the 50x150x5 mm solid shape memory elements could be tested both at 0 °C (thermal SME) and at 40 °C (SE). For the thermal SME, maximum accelerations of 3,76 m/s^2 with maximum displacements of almost 45 mm were measured, for the SE corresponding to 5,76 m/s^2 and 25,5 mm. However, no increase in temperature could be detected. It can therefore be concluded that SMAs have a high damping capacity and, depending on the application, the thermal SME or the SE provides better damping properties.

3.3. Automotive area

An overview of potential applications of SMAs in the automotive area can be found in many other papers [4, 6, 28]. Some of them have already been presented in certain demonstrators; others are still under development [24]. One application that already passed to a standard-production application in luxury class vehicles of some car manufacturers are the SMA pneumatic valves for lumbar support in car's seats.

This first high-volume product (>5 Mio actuators/year) is an automotive valve used to control low pressure pneumatic bladders in a car seat that adjust the contour of the lumbar support/bolsters. The overall benefits of SMA compared to traditionally-used solenoids in this car seat application (e.g.: lower noise, electromagnetic compatibility, lightweight, required space, power efficiency/consumption) are the crucial factors in the decision to replace the old standard technology with SMA.

According to the manufacturer [25] the SMA actuators are a perfect fit for valves because the micron thin SMA wire allows for numerous valve form factors enabling various options for attachment. In addition, the included proportional control (without any additional sensor) is the most suitable option for every valve supplier [25]. The silent and minimalistic design specification of the SMA air and gas valves offers benefits for a wide use in the automotive industry. This has contributed to winning significant production volume in the automotive sector [26]. This actuator is designed to fit into a customized valve or valve block offering 2 × 2/2 way, replacing two single magnets that would have to be used otherwise (see Fig. 2).

Fig. 2. SMA actuator with SmartFlex wires and electronic control board (left side). The SMA wire is conducted along the plastic part and activates the valve against the bias spring when heated (right side) [27, 28].

Some of the impressive actuator characteristics [27] are listed here: Voltage: 9–16 V; Temperature: −40°C–80°C; Stroke: 0,4 mm; Closing force: 0,8 N; Full open/close < 120 ms; Weight < 20 g; Noise < 25 dBa. One of the leading SMA companies is producing every year 10 million of these SM actuators that are installed in all main vehicles of Daimler, BMW, GM, Hyundai, Ford and Porsche/VW [28].

3.4. Aerospace and aviation

Probably the first commercial applications in the area of aviation are the SMA fasteners for the hydraulic tubes in the F-14 fighter jets in the 1970s [29]. Since then a variety of other applications were developed, e.g. structural connectors, vibration dampers, sealers, release or deployment mechanisms and also the pathfinder applications for the mars mission [30, 4]. These days more and more investigations are reported on active and adaptive structures in the sense that the airfoils can be modified to optimize various flight conditions [31, 32] or additional aerodynamic devices with SMA actuators can realize different conditions for jet engines [33], also known as variable geometry chevron, VGC. After the success of the VGC commercialization in Boeing 777-300 ER aircrafts, more research programs have been started by aircraft manufactures and related research agencies (e.g. Boeing, DARPA, NASA) to develop further such systems using SMA actuators [4, 34].

3.5. Area of consumer and electronic industry and area of household goods

The great variety of possible applications in this area is shown on the webpage of the Japanese Furukawa Electric Co., LTD [35]: SMA elements are used as temperature switchers in rice cookers and coffee makers as well as temperature adjusting elements in water mixing valves, anti-scald valves, bathtub adapters and air conditioners; superelastic shape memory elements are integrated in eyeglass frames and antennas; applications of superelastic SMA wires in dresses, brassieres and shoes were developed and they presented the world's first electrical current actuator SMA wire used in a MINOLTA auto focus single –lens reflex camera.

Another recent application in this field is a multifunctional autofocus camera module with optical image stabilizer for smart phones developed by the Actuator Solutions Company [36]. The very light and compact lens holder uses eight nitinol wires with a diameter of 25µm. They are actuated by electricity in order to create the required movements in z-direction for the auto focus (AF) function and in x- and y-direction, respectively, for the optical image stabilizer (OIS). The necessary control signals are given by gyroscope sensors that are integrated in smart phones, the reset movement is caused by bias spring force. Maximum movements of the lens with a diameter of 6,5 mm of 300 µm (AF) and 120 µm (OIS), respectively, are achieved in a few hundredths of a second. To prevent premature material fatigue only a fraction (1 to 2 %) of the maximum stretching capacity (5 to 6 %) is used. Compared to other systems using e.g. electrodynamic voice coils the SMA application is much smaller in design and consumes less energy. Annual quantities in the tens of millions appear realistic; the absolute market size is estimated at 400 million units [3/p.169].

3.6. Power engineering

By means of SMAs it is possible to transform thermal energy directly into a mechanical energy. If e.g. a NiTi SMA actuator wire with the OWSME is stretched in the martensitic phase the element can contract in austenitic phase when heated above the A_f-temperature. Under suitable conditions the element will exhibit a higher force or mechanical tension, respectively, in the austenite crystalline structure than in the martensite one. So it is possible to use heat of a solar heat exchanger or wasted heat of any process in combination with colder ground water to design a so-called solid state heat engine that is able to recuperate mechanical energy in low-temperature systems. This fascinating possibility has attracted many researches and companies to develop SMA heat engines designed for the power engineering area. Strong activities have been carried out in the 70s and 80s of the last century; reports about one of the first heat engines with nitinol [37] and an overview of other early engine types can be found in the proceedings of the Nitinol Heat Engine Conference from 1975 [38]. After a certain disappointment phase mainly due to low efficiencies and rapid material fatigue of the SMA materials used at that time it can be observed a growing research activity in this area during the last years. The authors of this paper are also engaged on the development of different heat engines with SMA since 1994 [8, 30, 39, 40] and have patented a new design [41].

In contrast to the previously patented tilted disk heat engine with SMAs, a current project is to make full use of the entire work output generated by the heating of the wire and the resulting change in the lattice structure in the axial direction. This means that the working power generated in the wire axis is temporarily stored by compressing a spring and later released outside the water bath just before the wire will be heated again in the next revolution. If this patent principle [41] can be implemented in a simple technical way, the efficiency of the heat engine will be increased and could advance the possibilities of energy conversion by means of SMAs.

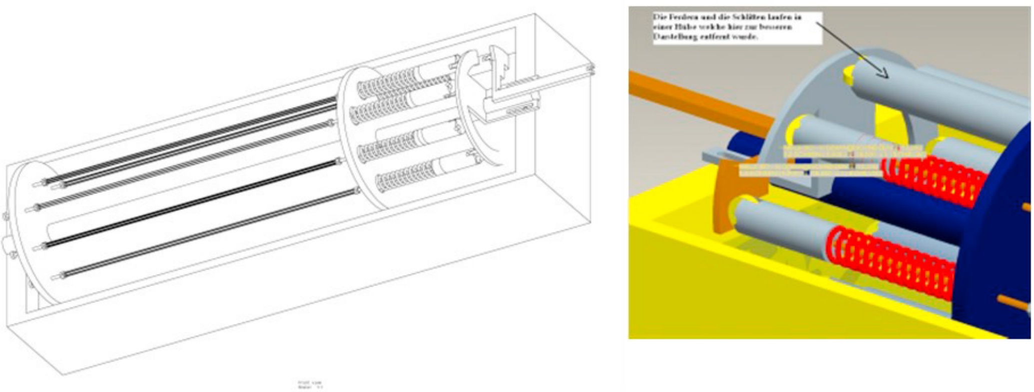

Fig. 3. Improved tilted disk heat engine with SMA a) general set up b) detail of the temporarily energy storage by means of a co-running raceway for energy accumulation [41].

Fig. 3 shows on the left side the overall sketch of the new type of thermal engine. SMA wires are fixed at an imaginary mantle line of a cylinder between two disks and are guided at one turn from a cold area (shown above, e.g. air) into a warm area (shown below as bath, e.g. filled with water). The solution approach of a "moving energy accumulator" is the new feature of this heat engine, which should lead to a significant increase in efficiency.

3.7. Automation and robotic area

In the area of robotic and automation SMAs find multiple applications because of their high power to weight ratio, the possibility of noiseless and sparkles activation of SMA actuators by electrical energy and the advantage to realize small and light designs. Additionally the sensor-function of shape memory elements can be used to give feedback signals of the actuator position. SMAs are used as miniaturized grippers, micro-actuators and artificial muscles for all kind of movements in industrial robots and even prosthetic hands [42, 43, 44].

4. New possibilities by using additive manufacturing with metal laser sintering technologies

During the development of products, it is usually helpful or necessary to depict intermediate development stages as prototypes. Especially in the case of cast components, this may cause some huge problems. In the worst case a new mold has to be created for each intermediate state. This can be both time- and cost-intensive. Machining of more complex components can reduce/destroy the memory effect and the manufacturing effort can be very high. In such cases, however, also for small series, additive manufacturing processes are particularly suitable, since they imply a high degree of geometric flexibility and do not require special moulds or tools. These are some of the reasons why additive manufacturing processes have grown significantly in recent years. Especially the metal additive manufacturing is rapidly expanding. In 2016, an estimated 983 metal additive manufacturing systems were sold. In 2017, that number shot up 80% to 1,768 [45]. Various investigations have also been carried out in the field of SMAs, especially NiTi, whereby they are mainly related to laser-sintering processes, e.g. selective laser melting (SLM).

In addition to the general advantages and limitations of additive production further points have to be considered for NiTi SMAs. In particular the laser-sintering process has a high influence on the materials properties. The processing parameters not only influence the porosity/density, the formation of the crystalline structure, the corrosion properties and so on, but also the shape memory properties such as the phase change temperatures, the effect size and the aging behavior. For this reason, it is particularly important for the laser sintering of NiTi to specifically set the processing parameters.

However, subsequent heat treatment usually is beneficial. For example, Dadbakhsh et al. [46] investigated the influence of production parameters on the phase change temperatures. For this purpose, two sets of parameters are defined in this study which achieve the highest possible relative density during the production of the samples. One parameter set was defined with a high laser power (250 W) and another one with a low laser power (40 W). The phase change temperatures of components produced according to these parameter sets are determined by using DSC measurements with a heating / cooling rate of 10 K/min. It can clearly be seen in Fig. 4 that the phase change temperatures are significantly different for each parameter set. These differences even remain after an annealing at 830 °C for 25 min under argon atmosphere and result in the fact that samples produced with a low laser power have higher phase change temperatures than samples produced with a high laser power.

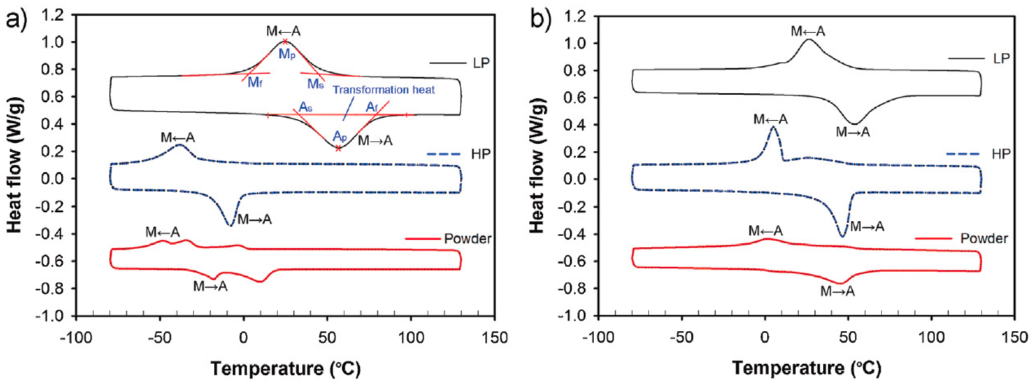

Fig. 4. DSC curves of NiTi samples (a) before and (b) after annealing of powder and two SLM parts. Shown are the 2nd cycling of heating and cooling. A heating and cooling rate of 10 K/min was used. [46]

In the study on effect size and cyclic stability by Meier et al. [47] the comparison between conventional NiTi and NiTi produced by SLM is presented. For this purpose, samples are produced with SLM parameters for dense parts. These samples are pressed and then thermally restored. This is carried out at two stress levels and with 15 cycles each. The stress levels are 400 MPa and 1200 MPa. Fig. 5 shows that the SLM NiTi with the manufacturing parameters used here has a smaller change in properties over the first 15 cycles than the conventionally produced NiTi. The diagrams shown in Fig. 5 illustrate that not only the cyclic stability for SLM NiTi is on a higher level, but also the reversible strain, both at 400 MPa and 1200 MPa. Accordingly, in every cycle number the irreversible elongation values of the SLM NiTi specimens are at a lower level than those of the conventionally produced specimens.

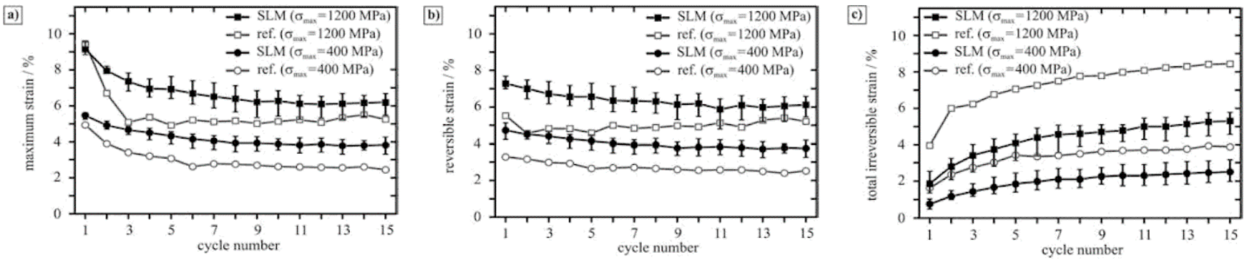

Fig. 5. Evolution of characteristic values during cyclic testing: max. strain ε_{max} (a); reversible strain ε_{rev} (b) and total strain ε_{irrev} (c). [47]

For the demonstration of a workable shape memory part produced by SLM, Meier et al. [47] tested a meandering actuator for functional characterization in a test facility. The used test facility allows the detection of elongation through an ultrasonic distance sensor and the detection of temperature through thermal imaging.

The actuator was elongated from an initial length of 22.5 mm to 31.5 mm in the martensitic state before implementation. A constant load of 10 N was applied during the thermomechanical testing and a constant electrical current of 10 A was used to heat up the actuator to approximately 440 K. With the constant bias load a reversible elongation of the actuator can be seen while cooling down and an almost complete recovery was achieved (Fig. 6).

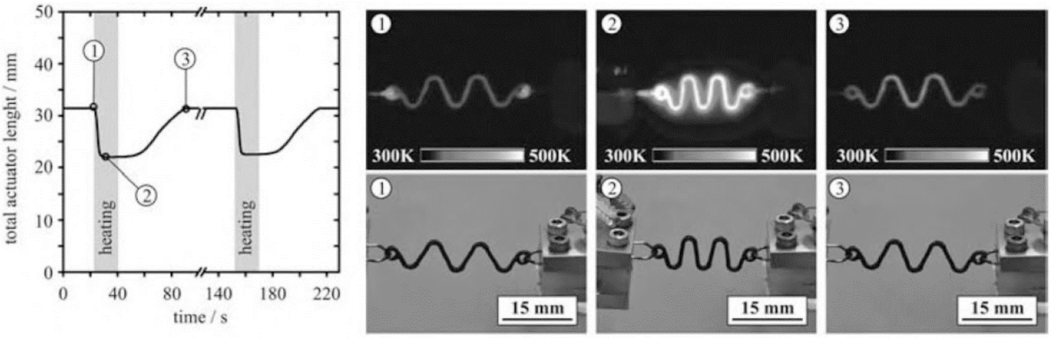

Fig. 6. NiTi SLM actuator showing a shape memory effect. Elongation plot (left), photographs and thermal images (right). Situation 1: elongated actuator, martensitic state prior to heating. Situation 2: contracted actuator, austenitic state during heating. Situation 3: elongated actuator, martensitic state after cooling down. [47]

By this short literature overview it can be stated, that nowadays it is possible to produce NiTi elements by SLM production technologies that have comparable or even better functional characteristics than conventionally produced NiTi. The meandering actuator demonstrates in an impressing way the possibility to create complex functional parts.

Additionally to the new possibilities for producing SMA NiTi parts there are some new guidelines for product development with SMAs from the VDI (The Association of German Engineers). In the past, only some few ASTM standards existed, e.g. the “Bend and Free Recovery” test for the determination of the transformation temperature of NiTi SMAs [48]. Furthermore the transformation temperatures of SMAs were normally characterized by differential scanning calorimetry, DSC. In both cases the main problem is that the values of the transformation temperatures are determined on unloaded samples. In the case of the DSC testing method the reliability and a comparison to other testing methods was very difficult in most cases, because the testing conditions (e.g. specimen weight, heating/ cooling rate) were not exactly defined. In order to avoid these problems, years ago a test facility was developed at the HTWG for testing shape memory elements under real working conditions, even tests against simulated spring forces and at different ambient temperatures are possible [49, 50].

The newly released VDI 2248 guidelines [51] are the first ones, as far as the authors know, that not only describe different material testing of unloaded specimens but also different component and system tests with SMA. Furthermore these guidelines describe not only test and measurement methods but also information for the simulation and model development.

With the combination of new SMA part production possibilities and the new guidelines for testing those parts with comparable conditions it is way easier to handle SMA in the product development and to transform them into commercial applications.

5. Summary and Conclusions

Thermal SMAs show extraordinary material properties and can be used as actuators, dampers and sensors. A short overview of the most important shape memory effects and the most important material properties are given for the SMAs of the NiTi group. In the style of a literature review that does not claim to be complete many examples for industrial applications are given. Although many of the applications shown here have not yet exceeded the threshold for a successful commercial use on the one side, the presented ready-to-market examples demonstrate their industrial application potential. However, the authors of this work are very optimistic that this will change in the near future and much more applications using these intelligent materials will be commercialized. This assessment is mainly based on two new tendencies:

First: the possibilities of the new production technologies, e.g. selective laser melting, will facilitate the manufacturing of shape memory elements for demonstrators, prototypes and even in small commercial series production. As shown in the last chapter, it is also to be expected, that in many cases these new production technologies will lead to even better properties, e.g. with regard to the effect size and lifetime.

Second: the German VDI guideline for SMAs introduced in 2017 will give the material a further boost in the industrial implementation of new applications.

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