

High Load Shape Memory Alloy Actuators: Design, Development and Application in Production Engineering

Andreas Hofer, Kai Thüsing, Kenny Pagel, Welf-Guntram Drossel

Abstract. The ongoing automation, customization, and flexibilization of manufacturing processes requires actuators that can actively influence manufacturing processes besides an increased use of sensors and improved connectivity between production steps and machines. In recent decades, novel actuators based on smart materials have gained importance in various application areas. Shape memory alloys (SMAs), as a prominent class of smart materials, exhibit the highest specific energy density among all solid-state actuation principles and offer exceptional scalability. Here, especially miniaturized SMA actuators are already being used in numerous applications, predominantly with forces up to 10 N. In contrast, this paper provides a comprehensive overview of the design, development and application of novel types of high load (HL)-SMA push-actuators with forces above 1 kN.

Recent advances in SMA actuators are reviewed, while focusing on innovative geometries and integration strategies for SMA components, along with their thermal, mechanical, and fatigue properties. In addition, advanced modeling approaches, such as finite element (FE) and simplified lumped parameter models, are evaluated for their ability to simulate, and optimize actuator dynamics. On top of this potential industrial applications of HL- SMA actuators are explored. Focusing here on where HL-SMA-actuator technology can improve force distribution, streamline adjustment processes, and enhance overall system reliability and performance. Cutting-edge manufacturing methods, including additive manufacturing of SMA components, are also highlighted, demonstrating significantly improved functional properties. Combining efficiency, adaptability, and sustainability, these HL-SMA actuators offer forward-looking solutions for a wide range of industrial applications.

Keywords: Shape Memory Alloys, High Load Actuators, Production Engineering, Machine Tools, Mechatronics, Smart Materials.

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1 INTRODUCTION

With the ongoing development toward Industry 4.0, industrial processes are becoming more and more automated and digitalized. This shift aims to increase efficiency, adaptability, and productivity, while enabling economical small-batch production, customization, and predictive maintenance. To achieve this, actuators are essential as they enable the physical manipulation of manufacturing processes, as shown by two examples in section 4, which were calculated based on sensor and model data. Here, especially actuator systems with high actuating forces in the kN range are crucial for several industrial applications. High-load (HL)-actuators based on thermal shape memory alloys (SMA) are most promising where commonly used actuators based on electromechanical, hydraulic, pneumatic, or piezoelectric technologies are limited.

SMAs are able to return their original shape after plastic deformation through thermal activation based on a martensitic phase transformation [1]. This effect enables SMAs to generate mechanical strains and stresses if constrained, with the martensite to austenite transformation. The reversible deformation in the martensite phase is usually achieved by a return spring. SMA actuators offer a high specific energy density, which enables extremely compact actuators and high forces. Thus, SMA are ideal for applications with limited installation space [1, 2]. SMAs have mostly been used as wire actuators in micro and small systems with actuation forces of up to a few Newtons. Large batch examples include pneumatic valves in the automotive industry [3] and optical image stabilization systems in smartphone cameras. The advantages of these systems are their small footprint, low weight and noiseless operation [3, 4]. Due to their excellent scalability, the development of HL- SMA actuators enables to design small actuator systems with high actuation forces for machine and process automation.

In recent years, HL-SMA actuators have already been investigated in several studies and been practically implemented in technical applications. Britz and Motzki investigated in [5] bundles of SMA actuator wires. By connecting 28 SMA wires in parallel they achieved actuator forces up to 1200 N. However, the space requirement is greatly increased by the large installation space required for the clamping elements. Another application is the breaking of rocks as part of geological investigations during space missions [2]. For this purpose, rod or tube actuators made of high-temperature SMAs are manually deformed, inserted into a borehole of the rock sample and subsequently heated. The forces are sufficient to fracture the rock sample. Due to the lack of passive reset elements a manual reset is necessary. Another example are torque tubes to generate torsional motion [6]. Such actuators are used in the aerospace industry for flap actuation, control of process fluids in thermal management systems or in adaptive aerodynamics to adjust wings or intake ducts. The max. torque depends on the geometry and specific operating conditions and can reach 1400 Nm [7].

The actuators presented can only be used for their specific fields of application and the adaptability to production machines is very limited due to installation space, one-way actuation or the type of generated force. Therefore, this paper focuses on HL-SMA push-actuator technology, which is characterized by high actuating forces of more than 1 kN, small space requirements, cyclic operation, simple control, and low acquisition and operating costs.

2 DEVELOPMENT OF HIGH LOAD SMA PUSH-ACTUATORS

2.1 Basic structure of HL-SMA push-actuators

The design of a suitable shape memory component (SMC) is crucial for the development of HL-SMA push-actuators. The selected SMC geometry is strongly dependent on the availability of SMA semi-finished products. Generally, SMAs are available as sheet, strip, rod, tube or wire. Wires are the most common SMA geometry and already used in large quantity in products.

The type of mechanical load (tension, compression, bending, torsion) determines the choice of SMC geometry. To cyclically utilize the shape memory effect (SME), local strains and stresses must remain below a critical threshold. In general, the highest material efficiency can be achieved by applying tensile and compressive loads [8].

While wire actuators are cost effective, they present a challenge for mechanical integration under high load conditions. The space required for clamping SMA wire bundles is disproportionately large compared to the actual actuator volume, as shown in the work of Britz and Motzki [5]. Compression-loaded actuators offer better miniaturization potential, since simple axial clamping eliminates the need for large connecting structures. Figure 1 (left) illustrates a schematic compression-loaded SMA actuator system.

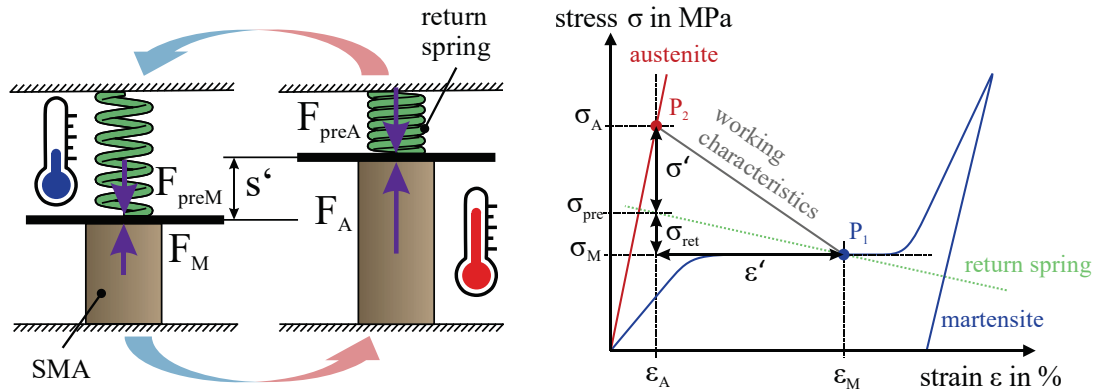


Figure 1: Structure of a compressed SMA actuator (left) and SSD for the design of SMA actuators (right)

2.2 Mechanical design

The mechanical properties of the SMC are critical. Stress-strain diagrams (SSDs) determine these properties in martensitic (low temperature) and austenitic (high temperature) states (see Figure 1, right). The operating points (P1: disabled, P2: enabled) define the usable stroke and force of the actuator. The effective actuator strain ϵ' is derived from the difference between the SMC strain ϵ_M in the deactivated (martensitic) state and the strain ϵ_A in the activated (austenitic) state, as expressed in Equation 1.

$$\epsilon' = \epsilon_M - \epsilon_A \quad (1)$$

Strain must not exceed 2% to achieve more than 10^5 actuation cycles [8]. Higher strain (up to 8%) increases structural degradation, causing actuator shortening if compression-loaded or

elongation and breaking if tension loaded. The effective usable actuator stress σ' is determined by the maximum austenite stress σ_A , the martensite stress σ_M , and the reset stress σ_{ret} of the reset element, as described in Equation 2.

$$\sigma' = \sigma_A - \sigma_M - \sigma_{\text{ret}} \quad (2)$$

As a rough design guideline, the maximum stress σ_A of 400 N/mm² should not be exceeded [8]. However, this limit varies depending on the semi-finished product used. Beyond the maximum stress limit, increased functional degradation is observed in the form of a reduction in the SME. This leads to a decrease in the reversible strain of the actuator.

2.3 Miniaturized HL-SMA push-actuators

Figure 2 shows two HL-SMA push-actuators using tubular SMCs. The right-hand design, introduced in [9], is a miniaturized evolution of the earlier concept from [10], integrating the spring return element as a Belleville washer pack inside the SMC to reduce overall package size.

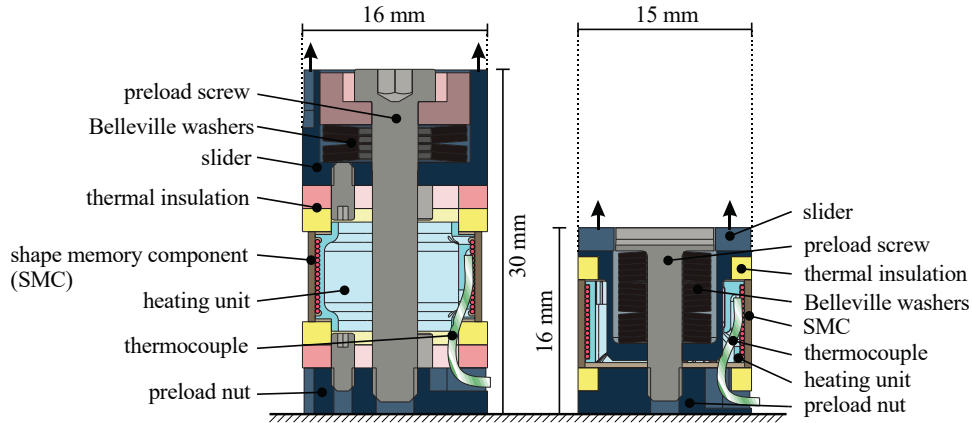


Figure 2: Structure of the HL-SMA push-actuators (left - based on [10], right - based on [9])

Both actuators share identical SMC dimensions: 15 mm outer diameter, 0.6 mm wall thickness, and 7.8 mm height in the austenitic undeformed state. A preload mechanism (slider, screw, nut, pack of Belleville washers) compresses the SMC in the martensitic state with a torque of 2.4 ± 0.1 Nm. The max. cold-state strain ϵ_M of 2% yields a theoretical displacement of 156 μm , with an actuation force of 8.86 kN at σ_A of 400 MPa. Actuator stroke can be increased to 180 μm for applications with cycling requirements of less than 10^5 cycles [9].

The tubular design allows for the integration of the heating unit and a thermocouple inside the SMC, in addition to improved thermal properties by maximizing the ratio of surface area to SMC volume. The heating unit consists of resistance wire wrapped around a temperature-resistant sleeve, with a thermocouple for temperature control. The ceramic thermal insulation minimizes heat loss to the surrounding components. For more dynamic cooling of the actuator, the ceramic disks can be replaced by discs with higher thermal conductivity. As a result, more energy is lost during heating; however, the surrounding structure acts as a heat sink.

2.4 Thermal design

In [10], the thermal simulation of HL-SMA actuators, using the actuator concept from Figure 2 (left) as an example, is performed using the finite element method (FEM) and a simplified lumped parameter model (LPM). The structure of the LPM used is shown in Figure 3 (left). The LPM simplifies the actuator system into four nodes with thermal capacitance C_i and temperatures ϑ_i of the actuator components.

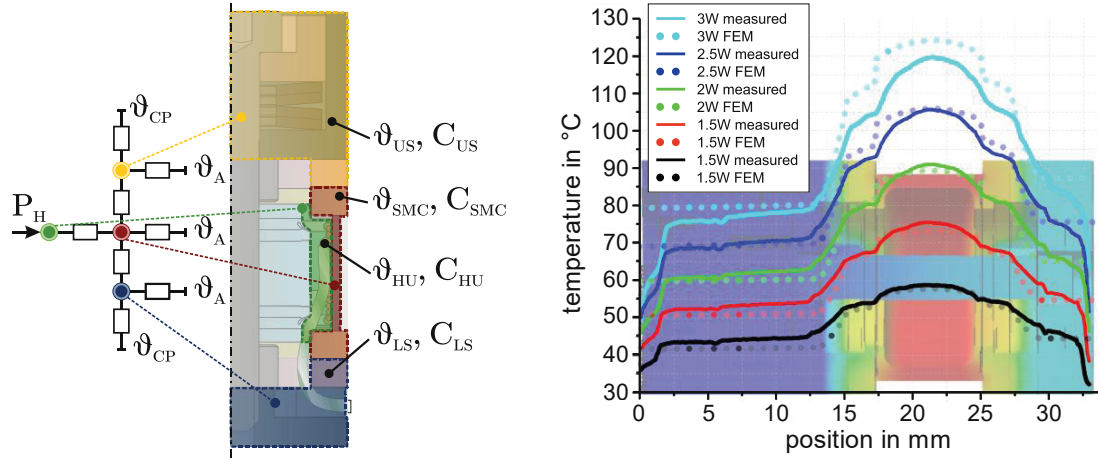


Figure 3: Structure of LPM (left, based on [10]) and comparison of experimental measurements and FEM simulation results (right)

Heat flow between nodes is modeled via thermal resistances $R_{th,ij}$, considering transfer, contact, and boundary effects. The model uses the temperature of the force-introducing planes ϑ_{CP} and ambient temperature ϑ_A as global conditions. The heating power P_H serves as an input parameter, determining the SMC temperature ϑ_{SMC} . FEM simulations provide model parameters based on the actuator geometry and material properties required for the LPM. The FE model describes the spatial temperature distribution and heat flows but requires specific assumptions for simplification due to long computation times. The LPM is a highly simplified model suitable for fast dynamic calculations. Both models have been validated in [10] with experimental data obtained from temperature measurements during the operation of the SMA actuator. Figure 3 (right) shows an exemplary comparison between experimental measurements and the FEM simulation. The validated models enable accurate and efficient thermal prediction, supporting real-time control and early-stage actuator design.

2.5 Control system

HL-SMA push-actuators are controlled by SMC temperature regulation. A resistance heating unit (Figure 4 - left) converts electric power into thermal energy to dynamically heat and activate the SMC. A graphite foil layer minimizes thermal resistance between the SMC and the resistance heating wire and allows friction reduced movement. An electrical heating power of maximum 22.5 W (15 V/1.5 A) is used to activate an HL-SMA push-actuator [11].

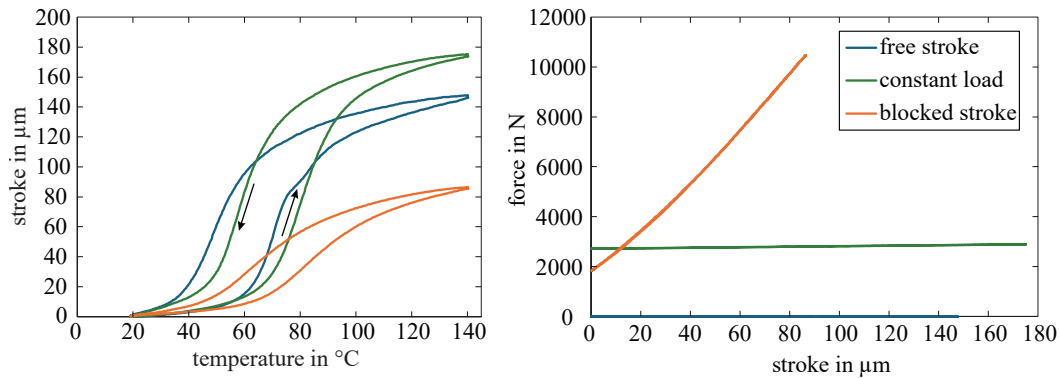


Figure 5: Stroke-temperature behavior (left) and force-stroke behavior (right) of HL-SMA push-actuator

In the blocked stroke scenario, the measured stroke corresponds to the compliance of the load screw. With an initial force of 1.9 kN, the HL-SMA actuator can generate actuating forces of more than 10 kN. The critical stress limit of 400 MPa, as defined in Section 2.2, corresponds to a force of 8.86 kN, which is therefore exceeded. Due to the high slenderness of the SMA cylinder, buckling occurs under such loads, as shown in Figure 6 (center) compared to the unloaded state (Figure 6 - left). This reduces both actuator life and performance by reducing the usable stroke. Buckling can be mitigated by using martensitic stops or limiting the maximum load.

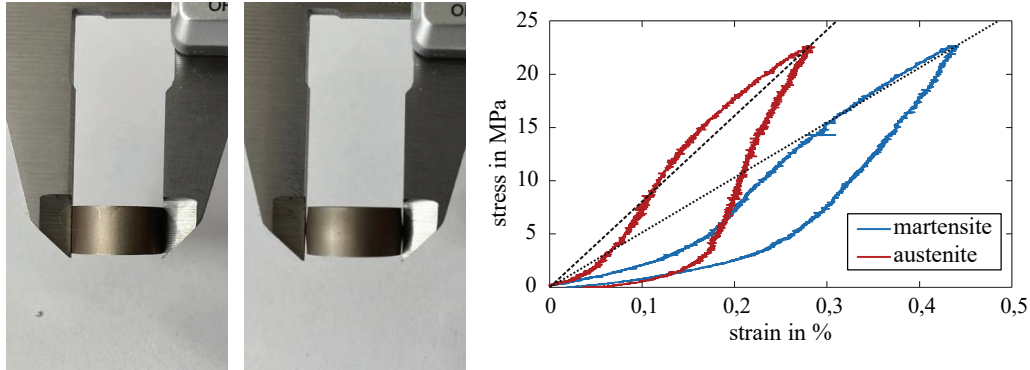


Figure 6: New and bumped SMC (left) and stress-strain-behavior of HL-SMA push-actuator (right)

In addition, higher actuator loads shift the phase transformation temperatures (PTTs) to higher ranges, indicating a stress dependence of the transformation. Consequently, the SMC requires higher temperatures for complete austenitic transformation at high operating loads. To ensure full activation of the SMA actuator during long-term operation, higher activation temperatures must be applied.

To further characterize the HL-SMA push-actuator, tests were performed using a *ZwickRoell* universal tensile-compression testing machine with a maximum force of 20 kN. The stiffness of the entire actuator system was investigated in both the deactivated and activated states. In

addition, the stiffness of the test machine without the actuator was measured, and the data were corrected accordingly. The measurement results for the actuator presented in [9] ($\varnothing 15\text{mm} \times 16\text{mm}$) are shown in Figure 6 (right).

Due to the phase transformation of the SMC, the actuator has a different average stiffness depending on the activation state: $89.17\text{ N}/\mu\text{m}$ when activated and $57.12\text{ N}/\mu\text{m}$ when deactivated. This variation must be considered when integrating HL-SMA push-actuators into manufacturing machines that require high stiffness.

3.2 Dynamic characteristics

A drawback of SMA actuators compared to other actuation technologies is their limited dynamic performance. Because the SME is thermally driven, actuation speed is limited by thermal inertia and the ability to rapidly heat and cool the material. Due to their much larger volume compared to wire actuators, HL-SMA push actuators have a larger thermal capacity which limits actuation frequency. Using a heating unit is a simple and space-efficient method of activating the HL-SMA push-actuator. However, it has the disadvantage of slow heating dynamics and lack of active cooling. Forced convection with compressed air or the use of fluid-based temperature control can improve dynamic performance.

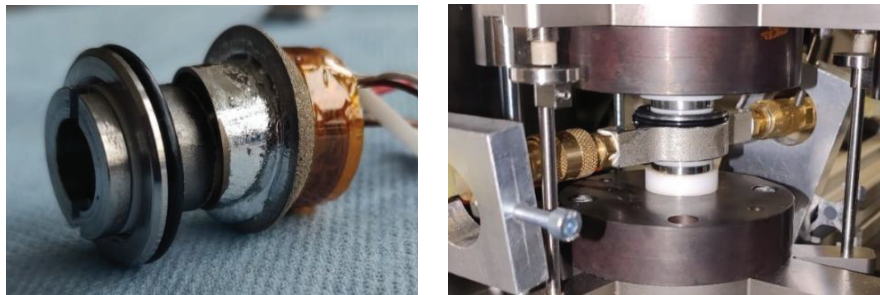


Figure 7: SMA actuator with liquid metal and sleeve (left) and dynamic test setup (right)

Figure 7 shows an example setup using an additively manufactured sleeve with integrated cooling channels. Liquid metal (*Thermal Grizzly Conductonaut*) is used to improve thermal conductivity between the sleeve and the SMC. Hot ($90\text{ }^{\circ}\text{C}$) and cold ($5\text{ }^{\circ}\text{C}$) fluids are alternately pumped through the two connectors of the sleeve. Figure 8 shows the dynamic behavior of different temperature control methods during heating and cooling of the actuator.

The experiments show actuation times (activation and deactivation) of 175 s with a heating unit and free convection, 45 s with a heating unit and forced air cooling using compressed air directed at the SMC, and 4.35 s with fluid-based temperature control, resulting in a maximum switching frequency of 0.23 Hz. The different actuator strokes result from slightly different preload forces. These forces are caused by limited accuracy during preloading due to the preload screw's torque specification.

These dynamic characteristics result in application limitations. HL-SMA actuators are generally not suitable for processes requiring switching frequencies above 1 Hz. In addition, their integration into technical systems becomes more complex and space-consuming when

high dynamics are required due to the need for additional components for fluid-based temperature control or forced convection.

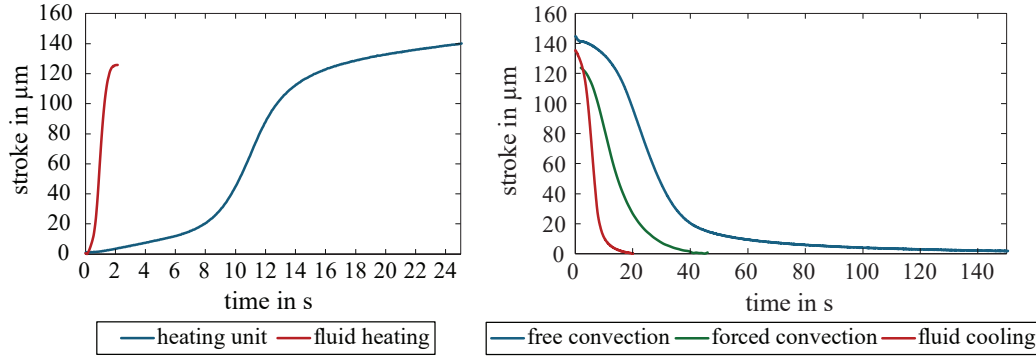


Figure 8: Heating and cooling characteristics with different temperature control methods

3.3 High load shape memory components

To the best of the authors' knowledge, there are currently no commercially available SMA tubular semi-finished products with PTTs for actuation purposes. As a result, hollow cylinders are typically cut from round-hammered ingots, which are intermediate products in SMA wire production and have inferior shape memory properties compared to the final wire product, resulting in reduced actuation performance and efficiency. In addition, manufacturing SMA hollow cylinders from ingots is cost intensive. Due to the poor machinability of SMAs, these cylinders must be cut using electrical discharge machining (EDM), a time-consuming and expensive process.

In [9], additive manufacturing is presented and compared as an alternative to conventional ingot-based SMC manufacturing. The base material was produced by *Ingpuls GmbH* and was a Ni42.5Ti50.0Cu7.5 (at.%) ingot. The additive specimens were produced using the laser powder bed fusion (PBF-LB/M) process. The base material was powder atomized from a Ni45.0Ti50.0Cu5.0 (at.%) ingot, also supplied by *Ingpuls GmbH*.

Figure 9 (left) shows a conventional and an additive manufactured SMC. HL-SMA actuators with conventional and additively manufactured SMCs were evaluated for their degradation behavior, specifically the cyclic stroke reduction and SMC shortening. Actuators with both additive and conventional SMCs were subjected to 10^4 load cycles. Figure 9 (right) shows the stroke-temperature behavior and shows significantly greater degradation and a more pronounced shift of PTTs to higher temperatures for conventionally manufactured SMCs. This highlights the superior stability and performance of additively manufactured SMCs for HL-SMA actuator systems.

A key advantage of additive manufacturing is the increased geometric flexibility in SMC design, which removes the previous constraints imposed by the size limitations of semi-finished products. However, the high costs associated with powder production and the PBF-LB/M process currently limit its feasibility to specialized applications with low production volumes. To improve actuator performance and cost efficiency, future research should focus on

optimizing SMA tubular semi-finished products, refining material processing, and exploring alternative manufacturing technology.

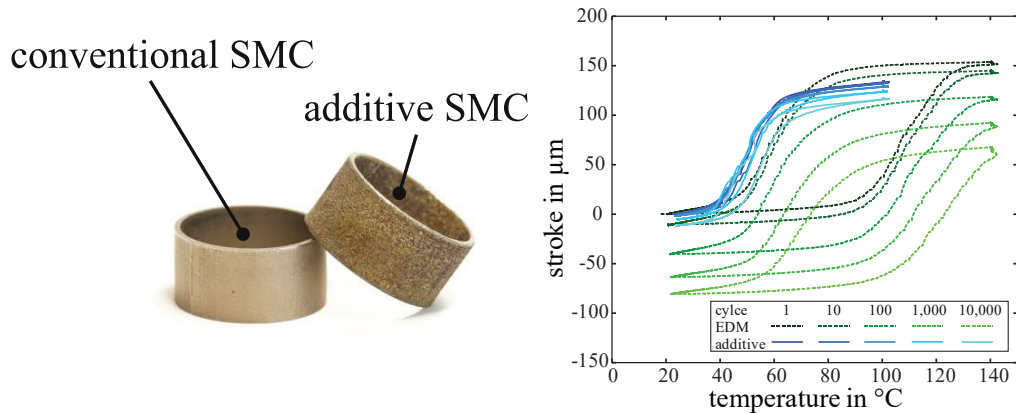


Figure 9: Conventional (EDM) and additive manufactured SMC (left) and comparison of stroke-temperature behavior (right, based on [9])

4 APPLICATIONS

HL-SMA actuators have significant potential to be utilized in production systems due to their advantages: high actuating forces, compact design, long service life, maintenance-free operation, easy integration into existing systems, scalable force and stroke ranges, low energy consumption, and low cost. However, their limited dynamics due to thermal inertia make them particularly suitable for applications requiring slow actuation or holding functions. Two practical applications for HL-SMA actuators are presented below.

In [12], an HL-SMA actuator system is presented for adjusting guide rails during the assembly of a machining center. The goal is to automate the previously time-consuming and costly manual alignment process. The main requirements for the actuators are high forces up to 10 kN, strokes up to 200 μm , and high positioning accuracy. Figure 10 shows the application concept (left) and the developed HL-SMA actuator (right).

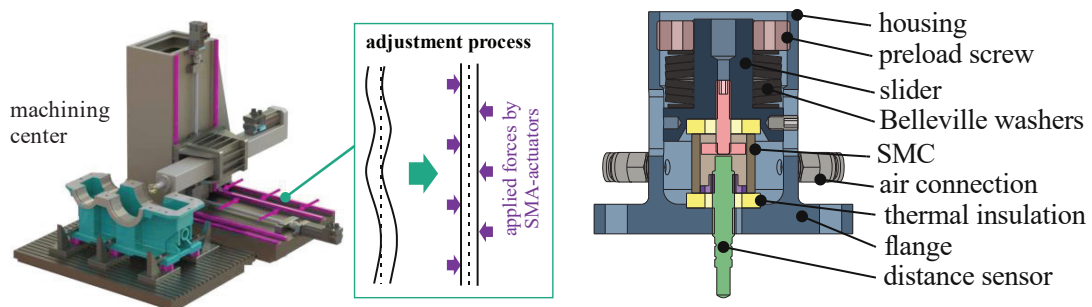


Figure 10: Application concept for automated fine adjustment of guide rails (left) and corresponding HL-SMA actuator concept (right) (based on [12])

Another application field is the use of HL-SMA actuators in deep drawing processes for sheet metal forming. In [11] and [13], a novel active blank holder is presented that allows real-time adjustment of the blank holder force distribution. The aim is to automate the try-out phase and actively compensate for process fluctuations to minimize scrap. Figure 11 shows a sectional view of the active blank holder with an integrated HL-SMA actuator (left) and the measured blank holder force distributions from deep drawing tests without and with the activated actuator array of 16 HL-SMA actuators (right). This demonstrates that the blank holder force distribution on forming tools can be actively controlled using HL-SMA actuators.

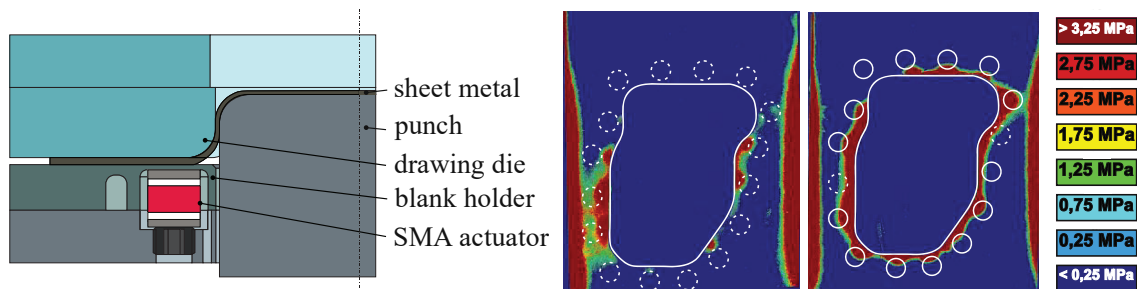


Figure 11: Sectional view of active deep drawing tool (left) and measured blank holder force distribution with deactivated and activated HL-SMA actuator array (right) (based on [13])

11 CONCLUSIONS

High-Load Shape Memory Alloy (HL-SMA) push-actuators provide a compact and efficient solution for industrial applications requiring high force actuation. This paper provides an overview of their development, properties, control strategies and applications. Optimized actuator geometries, improved manufacturing technologies such as additive manufacturing of shape memory components (SMCs), and insights into dynamic and cyclic behavior can improve performance and lifetime.

Experimental investigations have demonstrated actuation forces of more than 10 kN with minimal space requirements using an HL-SMA actuator concept. The scalability of HL-SMA push-actuators make them a suitable alternative to conventional actuators, especially in space-constrained environments. However, their low dynamics limits their use in high-frequency processes. Forced convection or active fluid temperature control can significantly improve dynamics, but at the expense of increased actuator size and cost. The limited stroke of HL-SMA linear actuators (up to 1 mm) makes them ideal for industrial applications such as fine positioning, holding or locking of tools and workpieces.

The application examples presented, including automated guide rail adjustment and adaptive blank holding in deep drawing, highlight their industrial relevance by improving efficiency, reducing manual intervention, and increasing system adaptability.

For large-scale industrial use, further research is needed on SMA tubular stock shapes, optimized SMC geometries to avoid buckling, and control strategies for continuous position and force regulation. By addressing these challenges, HL-SMA actuators will be able to support the next generation of automation and Industry 4.0.

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