SHAPE MEMORY ALLOYS

Smart Materials and Engineering
Made in Bochum
Introduction

Shape Memory Alloys (SMA) are special metal materials which have the ability to restore their initial shape after a severe deformation, they "remember" it. Technically relevant are mainly NiTi-based SMAs, i.e. alloys consisting of Nickel and Titanium, also known as “Nitinol”. Due to the functional properties of this material, it is a very suitable choice for actuator applications, but also parts which need to endure large reversible deformations (such as guide wires or catheters in biomedical applications). SMA combine actuator and sensor properties. With the highest energy density of all known actuator materials, they provide an enormous potential for weight reduction and energy efficiency. Pseudoelastic SMA can be deformed reversibly a hundred times more than conventional steels. NiTi-based actuators can lift up to a thousand times their own weight.
The underlying principle of the shape memory effect is a reversible solid state phase transformation between a low-temperature phase (Martensite) and a high-temperature phase (Austenite). Depending on the composition, the thermomechanical treatment and the ambient temperature, the shape memory properties of NiTi alloys can be separated into different characteristics.
One-way shape memory effect

The term “one-way shape memory effect” depicts the ability of an element to remember a predetermined shape by heating after an apparently plastic deformation. At the beginning, the microstructure consists of the low-temperature phase Martensite. A deformation of this initially twinned-martensite leads to microstructural changes (detwinning), making possible macroscopic strains of up to 10%. A subsequent heating causes the reverse transformation into the high-temperature phase Austenite. Due to microstructural changes, the element returns to its original shape, which is retained during cooling because of accommodation processes (repeated twinning).

Pseudoelasticity

In contrast to the one-way shape memory effect, pseudoelasticity describes a mechanical memory which can be programmed into the material. A pseudoelastic element has the ability to return to its predetermined shape after a (local) deformation of up to 10% without heating, just by unloading (rubber-like behavior). This effect can be observed if the Austenite is stabilized to operation temperature by specific alloying and/or heat treatment. The explanation of this phenomenon is a stress-induced phase transformation during loading and unloading.
**Materials and alloying systems**

Along with some ceramics and polymers which exhibit a shape memory effect under certain conditions, several copper- and iron-based shape memory alloys are known. But with nickel-titanium-based SMA (NiTi), considerably higher displacements and forces (actuator) can be reached. In addition, NiTi-SMA exhibit a higher functional stability in cyclic applications.

**Properties of SMAs**

NiTi-SMA exhibit an extreme reversible deformability (100x higher than that of steel), excellent structural and functional properties, a high corrosion resistance and a good biocompatibility. A further special feature is the high damping capacity of pseudoelastic alloys due to a stress-strain-hysteresis. As a functional coating, it improves the wear resistance against cavitation significantly. NiTi-SMAs are a very suitable choice for implants, because the mechanical properties are comparable to materials in the human body.
Application of SMAs

Due to the remarkable properties, applications of Ni-Ti-SMAs can be found in many technical fields. While the one-way shape memory effect is essential for the development of intelligent actuators in aeronautics and automotive engineering, pseudoelastic SMAs are predominantly applied in medical technology. The high flexibility, good corrosion resistance and biocompatibility have led to an increasing significance of SMAs in medical applications. Besides the best known use in medical technology as stents, SMAs are applied as guide wires or catheters in minimal invasive surgery or as orthodontic wires for tensioning dental braces. Beyond that, pseudoelastic components are used for vibration absorption or as solid state hinges.
SMA-actuators

SMA-actuators have a huge potential to successfully substitute a number of existing technical systems (e.g. piezolectric actuators, lifting solenoids or electric drives) by new approaches. As a result of the integration of SMA, these new products can be manufactured and operated more energy efficient, more intelligent and more economical. In contrast to present solutions, SMA provide the opportunity to design systems with higher displacements and forces as well as with a significantly smaller design envelope. The reduced quantity of necessary components decreases the failure probability of technical systems and leads to significant weight savings. In addition, SMA-actuators do not need a permanent power supply like e.g. electric drives, because they do not require electric power unless triggered.

The main advantages of SMA-actuators are:

- Large actuation displacement and recovery force
- High work output per unit of volume → compact powerful actuators
- Intrinsic sensory capabilities (in case of thermal actuation)
- Large energy absorption and damping capacity
- Non-magnetic
- Biocompatible and corrosion resistance
- Noiseless operation
- Low energy requirements
- Variable shapes and mechanisms
- Reduced system complexity and failure probability
PROPERTIES OF SMAS AND OTHER FUNCTIONAL MATERIALS

Advantages of SMA-actuators vs.

<table>
<thead>
<tr>
<th>Lifting solenoids</th>
<th>Bimetals</th>
<th>Electric drives</th>
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<tbody>
<tr>
<td>• Smaller design envelope</td>
<td></td>
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<tr>
<td>• Lower weight</td>
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<td>• Reduced energy requirements</td>
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<td>• Larger actuation displacements and recovery forces</td>
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<tr>
<td>• Smaller design envelope</td>
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<tr>
<td>• No stand-by energy consumption</td>
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<tr>
<td>• Lower costs</td>
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<tr>
<td>• Lower weight</td>
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</table>
Examples of different of SMA-actuator designs

<table>
<thead>
<tr>
<th>Contracting wire</th>
<th>Tension, compression spring</th>
<th>Laminar actuators made from sheets or bands</th>
<th>Coated substrates</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Contracting wire" /></td>
<td><img src="image2.png" alt="Tension, compression spring" /></td>
<td><img src="image3.png" alt="Laminar actuators" /></td>
<td><img src="image4.png" alt="Coated substrates" /></td>
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</tbody>
</table>

Possibilities of thermal activation

<table>
<thead>
<tr>
<th>Wire diameter</th>
<th>Recovery force</th>
<th>Wire length</th>
<th>Stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 mm</td>
<td>12 - 20 N</td>
<td>20 mm</td>
<td>1 - 1.6 mm</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>80 - 120 N</td>
<td>50 mm</td>
<td>2.5 - 4 mm</td>
</tr>
<tr>
<td>0.8 mm</td>
<td>200 - 305 N</td>
<td>100 mm</td>
<td>5 - 8 mm</td>
</tr>
<tr>
<td>1.0 mm</td>
<td>310 - 470 N</td>
<td>200 mm</td>
<td>10 - 16 mm</td>
</tr>
</tbody>
</table>

Exemplary specifications of a wire-actuator

<table>
<thead>
<tr>
<th>Resistance heating</th>
<th>Inductive heating</th>
<th>External heating elements (heating coil, PTC element)</th>
<th>Temperature control by environmental medium (air, water, oil, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5.png" alt="Resistance heating" /></td>
<td><img src="image6.png" alt="Inductive heating" /></td>
<td><img src="image7.png" alt="External heating elements" /></td>
<td><img src="image8.png" alt="Temperature control" /></td>
</tr>
</tbody>
</table>
The production of SMAs is a sophisticated process in which high standards of methodology, composition and purity are required in order to be able to fully exploit the unique properties of this material in applications. The design of parts and products based on SMAs is complicated by their non-linear mechanical behavior, which presents large difficulties for many engineers when dealing with SMAs.

Through years of experience in research and development, Ingpuls has the essential technological know-how necessary for the production, processing and application of SMAs.

As well as the production of these materials, we develop products, which can exceed their conventional properties by applying SMA. In addition, we support companies in successfully integrating this innovative material in their processes and products.
**PRODUCTS**

**Metallurgic melting products**
- High-purity SMA-ingots and experimental castings
- Binary, ternary and quaternary NiTi(X,Y)-SMAs (X,Y = e.g. Cu, Fe, Cr, V, Hf, Nb, Co, Mo, Zr)
- SMA-Sputter-Targets in customer specific geometries

**Semi-finished products**
- Wire, ribbon, sheet
- Different surface qualities
- Different dimensions and geometries

**SMA-components**
- Development of customized wire-, spring- and sheet-actuators
- Stress- and function-related design
- High functionality due to partiality configured SMA-components

**Functional coatings**
- Materials optimization by functional SMA-coatings
- Passive vibration damping
- Protection against cavitation
Product development and technical consulting

For the integration of SMA in products and processes, we support companies in all stages of the development process. Our services include the following:

### Alloy- and processing route development

For certain applications, standard alloys cannot meet the technical requirements. We develop new SMAs and optimize the production method and processing route to achieve the customer’s specific requirements (transformation temperature, mechanical properties).

### Technology transfer

We support our customers in developing well-founded knowledge about SMA in order to establish new technologies and materials in their companies on a sustainable and long-term basis. To achieve these goals, we offer different services which are tailored to the customer’s needs.
Finite-Element-Simulation

- Stress and deformation analysis
- Proof of strength
- Contact mechanics
- Simulation of pseudoelastic SMA-components

Development of unique testing techniques

The testing of new developed products and actuators requires solutions that are individually adjusted to that product. Fully automated test sequences, data visualization and analysis as well as a high user operating comfort and the possibility of integration in existing manufacturing workflows are the main benefits of our solutions.

Materials characterization

Utilizing the latest processes and technologies in the field of materials characterization, we develop new products or optimize existing products.

- Microscopy (LM, SEM incl. EDX-analysis)
- Fractography
- Surface analysis (surface roughness)
- Calorimetry, dilatometry
- Thermomechanical characterization
Industries

The Shape-Memory-Technology can be applied in nearly all industries, where components with as little weight as possible and a low energy consumption have to deliver a high performance.

Also improve the performance of your products with SMA!
<table>
<thead>
<tr>
<th>Biocompatibility</th>
<th>Adaptive play adjustment</th>
<th>Corrosion resistance</th>
</tr>
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<tbody>
<tr>
<td>Vibration damping</td>
<td>Actuator and sensor at the same time</td>
<td>Cost reduction by materials efficiency</td>
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