

Shape Memory Alloys (SMA)

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Abstract

This report introduces Shape Memory Alloys, describes properties of SMA as an actuator and introduces some available commercial SMA actuator products.

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1. Introduction

This section presents brief history of SMA actuators. Next in Section 1.2, the basic operation principle of SMA is given. Shape setting in NiTi alloys is discussed. The section ends with an introduction of a two-way Shape memory effect and superelasticity.

1.1 Brief history of SMA [1]

A Swedish physicist Arne Olander discovered “the Shape Memory Effect” (SME) in gold-cadmium (AuCd) alloy in 1932. The alloy could be deformed when cool and then heated to return to original “remembered” shape. The metal alloys with SME are called “Shape Memory Alloys” (SMA). In 1958, SME was demonstrated at the Brussels World’s Fair, where the SME was used to cyclically lift a load mass. Researchers of U.S. Naval Ordnance Laboratory found SME in nickel-titanium (NiTi) alloy in 1961 by accident, while studying the heat and corrosion resistance of NiTi. Today, the NiTi alloys are commonly referred to as “Nitinol”, for NiTi Naval Ordnance Laboratory.

The benefits of NiTi alloys, such as lower costs, smaller dangers (from health standpoint) and easier manufacturing and machining methods refreshed the interest in SME and its applications. In 1970’s, commercial products began to emerge. First devices were static, taking advantage of a single dimensional change, for example fasteners, couplings and electrical connectors. Then, SMA devices started to perform dynamic tasks as actuators. Ambient temperature-controlled valves and clutches were the first applications, later actuators with resistive heating and thus electrical control were proposed to be used in micro-robotics, for example. More sophisticated devices are studied continuously, for example [2, 3, 4].

1.2 Principle of operation [1]

Shape Memory Alloys, for example Ag-Cd, Au-Cd, Cu-Al-Ni, Cu-Sn, Cu-Zn-(X), In-Ti, Ni-Al, Ni-Ti, Fe-Pt, Mn-Cu and Fe-Mn-Si alloys, are a group of metallic materials having ability to return to a previously defined shape when subjected to appropriate thermal procedure.

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 the transformation temperature. Figure 1 is a simplified representation of material's crystalline arrangement during different phases.

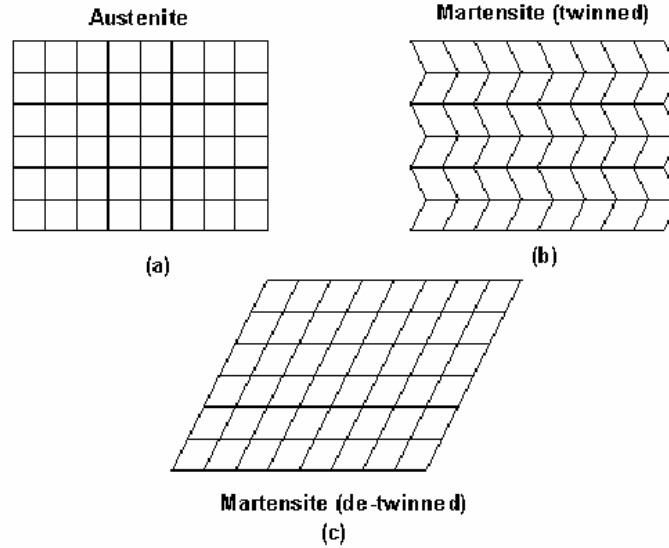


Figure 1: Crystalline arrangement of SMA in different phases.

In austenite phase, the structure of the material is symmetrical; each “grain” of material is a cube with right angles (a). When the alloy cools, it forms the martensite phase and collapses to a structure with different shape (b). If an external stress is applied, the alloy will yield and deform to an alternate state (c). Now, if the alloy is heated again above the transformation temperature, the austenite phase will be formed and the structure of the material returns to the original “cubic” form (a), generating force/stress.

An example of an SMA wire is represented in Figure 2. If the wire is below the transformation temperature (and therefore in the martensite form), it can be stretched with an external stress. Now, if the wire is heated to austenite phase, it will generate force/stress and recover the original, shorter, shape.

Also, hysteresis and non-linear behaviour are seen from Figure 2. The change in the SMA crystalline structure is not thermodynamically reversible process due to internal frictions and creation of structural defects. When heated, SMA follows the upper curve, A_s is the temperature, where austenite phase starts to form and in A_f the material is 100 % austenite. When the alloy cools, it follows the lower curve: M_s is the temperature, where martensite starts to form and in M_f the alloy is 100 % martensite.

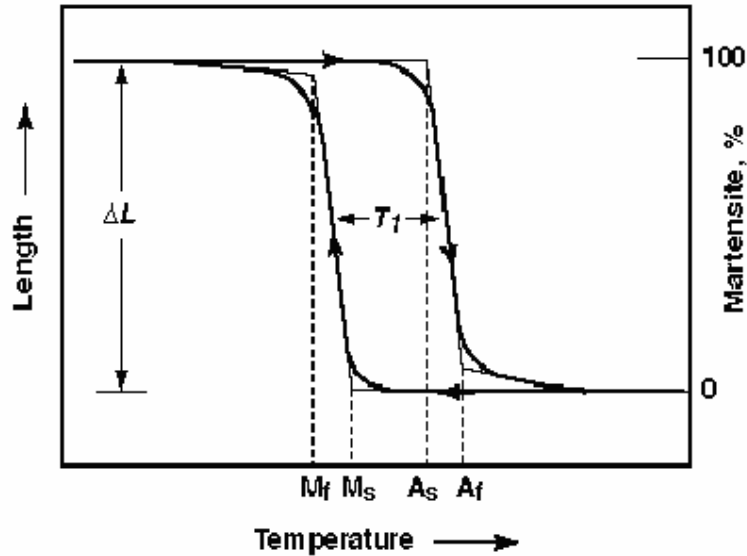


Figure 2: Contraction of an SMA wire as a function of temperature.

1.3 Shape setting in NiTi alloys [5]

The Shape Memory Effect must be “programmed” into the SMA alloys with an appropriate thermal procedure. Basically the procedure is simple; the alloy is formed into desired austenite form and heated into a specific temperature. The temperature and the duration of the heating depend on the alloy and the required properties.

For a NiTi alloy, a temperature of 400 °C and heating duration of 1...2 minutes can be sufficient, but generally 500 °C and over 5 minutes are used. Higher heat treatment times and temperatures will increase the actuation temperature of the element and often give a sharper thermal response, but may reduce the maximum output force.

Although straightforward procedure, the parameters for the heat treatment are critical and often require experimental determination before the requirements can be met.

1.4 Two-way Shape Memory Effect [6]

The ability of SMA to recover a specific shape upon heating and then return to an alternate shape when cooled (below the transformation temperature) is known as two-way shape memory. However, there are limitations that reduce the usability of the two-way effect, such as smaller strains (2 %), extremely low cooling transformation forces and unknown long-term fatigue and stability. Even slight overheating removes the SME in two-way devices.

Setting shapes in two-way SMAs is a more complex procedure than the one used with one-way SMAs.

1.5 Superelasticity [7]

SMA also shows a superelastic behaviour if deformed at a temperature which is slightly above their transformation temperatures. This effect is caused by the stress-induced formation of some martensite above its normal temperature. Because it has been formed

above its normal temperature, the martensite reverts immediately to undeformed austenite as soon as the stress is removed. This process provides a very springy, "rubberlike" elasticity in these alloys.

Because the superelastic behaviour is not usable in actuators, it is not described in details. As an example, the superelastic alloys are used in eyeglass frames. Figure 3 presents DuraFLEX eyeglasses.



Figure 3: DuraFLEX eyeglasses.

2. SMA as an actuator

The properties of SMA as an actuator can be divided into advantages and disadvantages rather clearly. On the other hand some properties must be categorized according to a specific application. Also the properties vary between different alloy compositions. The properties are discussed in the following Sections, from 3.1 to 3.8. The focus is on the NiTi alloy, because this alloy is the most widely used and considered as the most suitable alloy in engineering applications [1].

2.1 Force and Deformations

The greatest advantage of the SMA material is the availability of a large force from very small element dimensions and weight. Table 1 shows some properties of commercially available "Flexinol" NiTi alloy SMA wires, manufactured by DYNALLOY, Inc. [9]. It can be seen that a ≈ 0.38 mm (0.015") diameter wire can generate a pull force of ≈ 2000 g (≈ 19.5 N), for example. This gives about 170 N/mm² stress (force per cross-sectional area).

Table 1: Properties of Flexinol wire (NiTi alloy).

Diameter Size (Inches)	Resistance (Ohms/Inch)	Maximum Pull Force (gms.)	Approximate* Current at Room Temperature (mA)	Contraction* Time (seconds)	Off Time 70° C Wire** (seconds)	Off Time 90° C Wire** (seconds)
0.0015	21.0	17	30	1	0.25	0.09
0.002	12.0	35	50	1	0.3	0.1
0.003	5.0	80	100	1	0.5	0.2
0.004	3.0	150	180	1	0.8	0.4
0.005	1.8	230	250	1	1.6	0.9
0.006	1.3	330	400	1	2.0	1.2

0.008	0.8	590	610	1	3.5	2.2
0.010	0.5	930	1000	1	5.5	3.5
0.012	0.33	1250	1750	1	8.0	6.0
0.015	0.2	2000	2750	1	13.0	10.0

Theoretically, a force generated by any shape/size SMA element can be calculated from maximum stress generated by the SMA material.

SMA alloys provide a large deformation, compared to other active materials. Maximum deformation is approximately 7...8 % for NiTi element. The effects of cycling (repeated use) to maximum deformation are described in Section 2.5. Table 2 shows some properties of different alloys, manufactured by Advanced Materials and Technologies (AMT). It can be seen that the normal recommended deformation is from 3.2 % (NiTi) to only 0.8 % (Cu-Zn-Al).

Table 2: Properties of different SMA alloys (by AMT).

ITEM	Ni-Ti	Cu-Cu-Zn-Al	Cu-Al-Ni
Melting point (°C)	1250	1020	1050
Density (Kg/m³)	6450	7900	7150
Electrical Resistivity ($\Omega \cdot m \cdot 10E-6$)	0.5-1.1	0.07-0.12	0.1-0.14
Thermal Conductivity, RT (W/m*K)	10-18	120	75
Thermal Expansion Coeff. (10E-6/K)	6.6-10	17	17
Specific Heat (J/Kg*K)	490	390	440
Transformation Enthalpy (J/Kg)	28,000	7,000	9,000
E-modulus (GPa)	95	70-100	80-100
UTS, mart. MPa)	800-1000	800-900	1000
Elongation at Fracture, mart. (%)	30-50	15	8-10
Fatigue Strength N=10E+6 (MPa)	350	270	350
Grain size (m*10E-6)	20-100	50-150	30-100
Transformation Temp. Range (°C.)	-100 to +110	-200 to +110	-150 to +200
Hysteresis (K)	30	15	20
Max one-way memory (%)	7	4	6
Normal two-way memory (%)	3.2	.8	1
Normal working Stress (MPa)	100-130	40	70
Normal number of thermal cycles	+100 000	+10 000	+5 000
Max. Overheating Temp. (°C)	400	150	300
Damping capacity (SDC %)	20	85	20
Corrosion Resistance	Excellent	Fair	Good
Biological Compatibility	Excellent	Bad	Bad

2.2 One-way force

As an actuator, the SMA element can only provide force/displacement in one direction. For example, a wire that compresses when heated does not expand without external force, when the alloy cools down. This is one disadvantage of the SMA actuators. A bias (return)

mechanism must be used, if actuator has to be returned to the original (cold) shape after the heating phase. Figure 4 shows possibilities for generating the bias force.

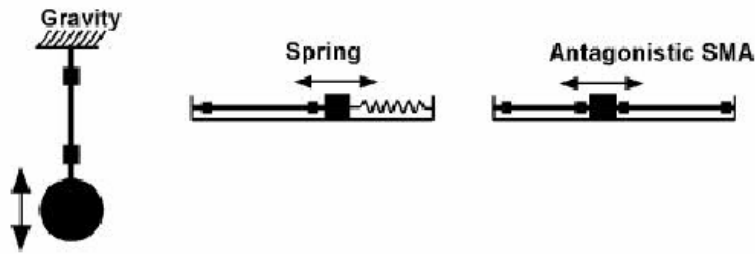


Figure 4: Bias mechanisms in SMA actuators.

The bias mechanism is usually implemented with a conventional spring, for example with a standard steel coil spring. The bias mechanism requires space, increases the weight of the actuator and the mechanical design becomes more complex. It must also be noted that the net output force decreases, because the force of the bias mechanism opposes the force of the SMA element.

If possible, a load force can be used as bias force. In Figure 4, gravity is used as an example of a load force as a bias force. The load force has to be large enough at all times, otherwise the actuator remains in the austenite position, even if heating is deactivated.

Another method to generate the bias force is to use an actuator that has SMA elements operating in both directions of movement. This is referred to as “an antagonistic SMA”. This provides output force to both directions, but the heating and cooling of opposing elements must be arranged properly. For example, if one element has been heated and then immediately after this an opposing element is heated, the first element resists the movement of the second, before the first element cools down enough. Also, if the elements are very close to each other, the heat transfer between elements can generate undesired forces.

There have been studies of “two-way” Shape Memory Effect that could provide force in both heating and cooling phases. This would remove the need for a bias mechanism. Due to restrictions of two-way memory (Section 1.4), it is recommended that one-way devices with return (bias) mechanism are preferred instead of two-way devices [7].

2.3 Cycling effects

Cycling (repeated use) affects the properties of the SMA. This must be considered when actuators are designed for a repeated/continuous use. Cycling causes the maximum available deformation, force and hysteresis to decrease, while the transformation temperatures increase gradually.

The reduction in the maximum strain and output force must be taken into account when actuators are designed. For NiTi alloys, only 2...3 % strain and stress level of 100...150 MPa are available after 100 000 cycles.

2.4 Hysteresis and non-linearity

SMA materials have a non-linear behaviour with a large hysteresis, as can be seen in Figure 2. This is a major setback when actuators are designed. If the movement of the

actuator has to be controlled, for example the displacement of an actuator generating linear movement, hysteresis and non-linearity cause difficulties. Therefore, many SMA actuators are “on/off” controlled, having only two positions of movement. This is easily obtained with continuous heating to maintain totally austenite phase or continuous cooling to obtain totally martensite phase.

Amount of hysteresis depends on the alloy composition, as can be seen in Table 2. Typical values for hysteresis in NiTi alloys are 25...50 °C [10].

In some applications hysteresis can be beneficial, as in a temperature control thermostat. When temperature raises enough, the SMA deactivates heating or activates cooling. Hysteresis prevents immediate “on/off” toggling of heaters/coolers and creates a proper thermostat function.

2.5 Temperature control of SMA element

Because the SMA effect is based on the temperature changes of the SMA material, the SMA actuators must have a method for controlling the temperature of the SMA element. Heating and cooling solutions and their properties are described in following Sections, 2.6.1 to 2.6.3.

2.5.1 Heating of SMA element

The heating of the SMA element can be accomplished with several methods by an electric current fed through the alloy, a separate heater element or heating with ambient material. These provide convenient and flexible possibilities for controlling the temperature of the alloy.

The heating with current (“Joule heating”) gives effective control over the temperature and therefore force and displacement. Although the concept is simple, it has two disadvantages. First, the resistance of the SMA is small (metal alloy). This causes the requirement for a large heating current, Table 1 shows some currents for different “Flexinol” wire sizes, for example 2.75 A is needed for a 0.38 mm wire. A current supply able to provide enough current increases the overall size and costs of the actuator system. Secondly, the heating current must flow through the SMA element, not through other conductive parts near or in contact with the SMA element. Therefore, the SMA must be electrically isolated from the surrounding environment. This causes special requirements for the components of the actuators.

Both DC and AC current can be used in heating. If AC is used, the frequency must be high enough to prevent oscillation in the SMA element temperature, which would cause oscillation of the actuator displacement and force. With AC, the heating effect depends on the root-mean-square (RMS) value of the current.

A separate heater element can overcome the difficulties of large currents used with the current heating method. A resistive heater element can provide enough power with smaller currents due to possibility to use larger voltage. On the other hand, a separate heater requires more components and additional space around the SMA element, also the total weight of the actuator increases. A heater element increases the cooling cycle time (Section 2.6.2) due to additional heated mass.

If the ambient material is used for heating (without any active elements), the SMA element operates according to the ambient temperature. This gives a possibility to use SMA as an ambient temperature controlled actuator, for example a heating thermostat controlling the

heating or cooling of ambient material. This is a very effective method, because in this case the SMA operates as an integrated actuator and a sensor, without any electric connectors.

2.5.2 Cooling of SMA element

The cooling of SMA element can be done with ambient material, requiring that the ambient temperature is lower than the transformation temperature range of the SMA element.

This method is useful, if the speed/band-width requirements are not critical. When the ambient temperature is close to the transformation temperatures, the cooling is slow. On the other hand, smaller heating current is needed to increase temperature to achieve the austenite phase. If the ambient temperature is much lower than the transformation temperatures, the cooling is quicker, but larger heating currents are needed.

Active cooling elements are needed if it is necessary to lower the temperature quickly or the ambient temperature is too high to achieve temperatures low enough to achieve martensite phase.

Forced convection cooling (with a fan, for example) is a relatively easy method for active cooling. Also cooling with moving liquid can be used in some applications. However, it must be noted that more powerful cooling system increases the required heating current, if the cooling is active continuously.

2.5.3 Peltier elements, integrated heating and cooling

One method for achieving active heating and cooling capacity is to use Peltier elements. These elements can heat or cool the SMA element, depending on the polarity of the voltage fed into the Peltier element. This method is useful, if both heating and cooling cycles must be quick. On the other hand also Peltier elements require space and create additional weight to the actuator entity.

2.6 Raw material

The raw material for SMA elements is inexpensive, especially NiTi alloy having only two component metals. It must be noted that the actual price for a complete SMA actuator depends on the other components and devices needed to create a proper actuator. Current supplies, Peltier elements, required measurements/sensors and other components that must be used set the total price, not the SMA material/element.

The corrosion resistance of NiTi alloys is excellent (comparable to stainless steels), providing a possibility to use SMA in environment with high humidity or even water. Also the biological compatibility of NiTi is excellent.

3. Shape Memory Alloy device examples

There are quite a few devices utilizing SMA commercially available. Some of these are described in Sections 3.1 to 3.6 to give a brief overview of possibilities.

Raw material for SMA elements is available from several companies, as well as ready-to-use (heat treated) SMA wires, expanding and contracting springs, and superelastic tubes. A list of manufacturers supplying SMA materials, elements or actuators is given in Section 3.7.

3.1 Frangibolt non-explosive release mechanism for spacecrafts [11]

The Frangibolt release mechanism by TiNi Aerospace, Inc. is designed for spacecraft to provide safe and controllable deployment of spacecraft payloads. Utilizing an expanding SMA cylinder with integrated heater element, the device is able to break the bolt connecting the load to the spacecraft. The release is therefore possible without explosives. Several different models for different bolts and payload weights (up to 5000 lbf/2300 kg) are manufactured. The device is re-usable after compression of the SMA element with external tool.



Figure 5: Frangibolt non-explosive release device.

3.2 Pinpuller non-explosive release mechanism for spacecrafts [12]

The pinpullers, also manufactured by TiNi Aerospace, Inc., are SMA wire actuated devices designed for securing and releasing of payloads in spacecrafts. As Frangibolt, the pinpullers offer small size, re-usability, reliability, safety and efficiency.

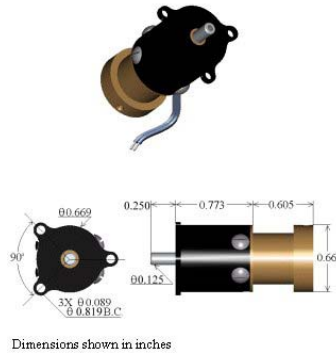


Figure 6: Pinpuller release mechanism.

3.3 Proportional pneumatic microvalve [13]

TiNi Alloy Company manufactures a pneumatic microvalve using TiNi thin film. The valve is able to control the airflow proportionally, replacing a conventional solenoid valve. Although in a prototype phase, the commercial distribution of the device should start soon.

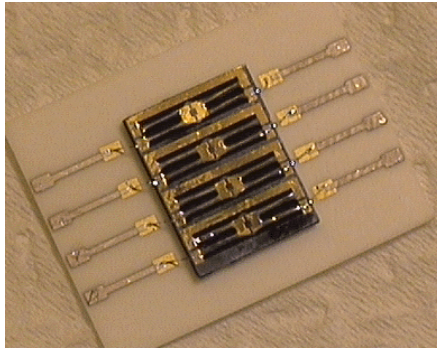


Figure 7: An array of four microvalves, the size of the array is 12.5 mm x 15 mm.

3.4 SMA actuated microrobots [14]

Japanese Toki Corporation has designed several microrobots utilizing SMA wires. IR controlled 8-legged microrobot, IR controlled microsubmarine, Micro Arm Robot and others have been constructed, but not sold commercially. Toki has developed an own SMA material called “BioMetal” [15].

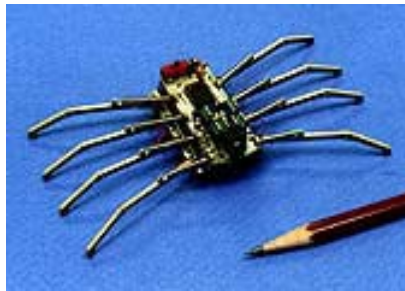


Figure 8: 8-legged microrobot with BioMetal wires.

3.5 Linear SMA actuator [16]

Advanced Materials and Technologies Corporation has several actuators driven by SMA elements, including an actuator generating linear movement and a maximum of 30 N force with a NiTi spring. More devices can be found from their web site.

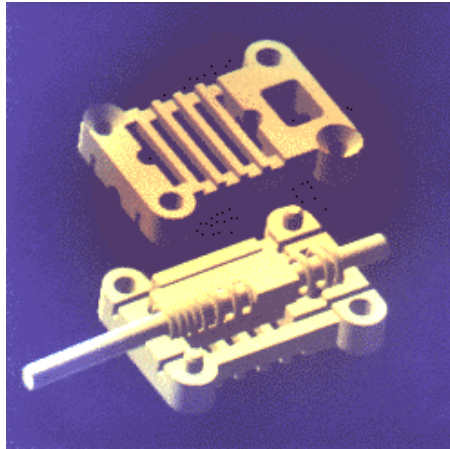


Figure 9: A linear NiTi actuator by AMT.

3.6 Medical devices

There are many applications in medical field. For instance: dental archwires, microsurgical tools, microgrippers, stents, catheters, guiding wires for catheters, implants

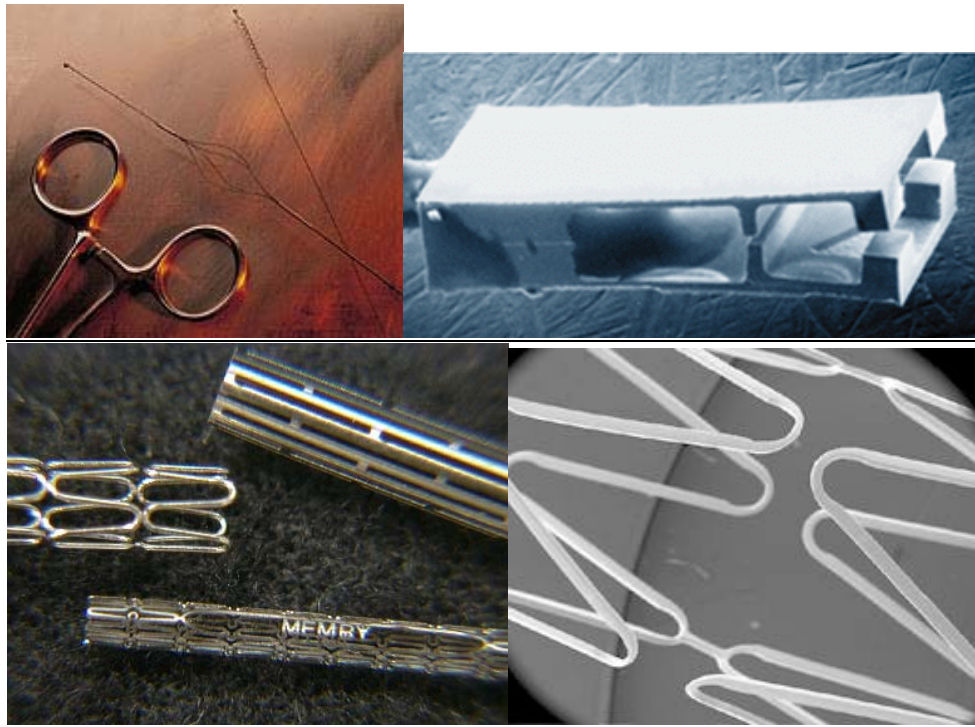


Figure 10: Surgical tools, microgripper and stents.

3.7 A list of SMA companies

Advanced Materials and Technologies (AMT), Belgium, www.amtbe.com

DYNALLOY, Inc., USA, www.dynalloy.com

Memry Co., USA, www.memry.com

Microfil Industries SA, Switzerland, www.microfil.ch

Mide Technology Co., USA, www.mide.com

Nitinol Devices & Components, USA, www.nitinol.com

Shape Memory Applications, Inc., USA, www.sma-inc.com

Special Metals Co., USA/UK. www.specialmetals.com

TiNi Aerospace, Inc., USA, www.tiniaerospace.com

TiNi Alloy Co., USA, www.sma-mems.com (www.tinialloy.com)

Toki Corporation, Japan, www.toki.co.jp

Ultimate NiTi Technologies, USA, www.ultimateniti.com

4. Conclusions

SMA materials offer interesting possibilities for actuator applications. The benefits such as, a large force with small dimensions and weight, a large deformation and relatively simple heating and cooling arrangements give opportunities to design micro-scale devices. On the other hand, the disadvantages such as, the requirement for a bias mechanism, large heating currents, long cooling times, cycling effects and non-linear due to the deformation hysteresis and drift reduce the overall competitiveness of SMA actuators.

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- 14 Advanced Materials and Technologies, *Use of Shape Memory Alloys –Actuators: Applications*, <http://www.amtbe.com>. 26.7.2001.