Composite Materials
(복합재료특론)

10 – Smart Composites

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10-1. Definition of Smart Materials

A smart or intelligent material refers to the material which has intrinsic sensing, actuating and controlling or information-processing capabilities in its microstructure.

Smart materials can be defined at three levels :

1. A material or a structure is said to be "sensitive" when it includes sensors providing information concerning the material itself or its environment to the system (zone A).
2. A material will be "adaptable" if integrated actuators can modify its characteristics (zone B).
3. The combination of these two properties (zone C) results in an "adaptive" material which collects data related to changes in its environment or its own damage, processes the collected data, and reacts through its actuator's action.

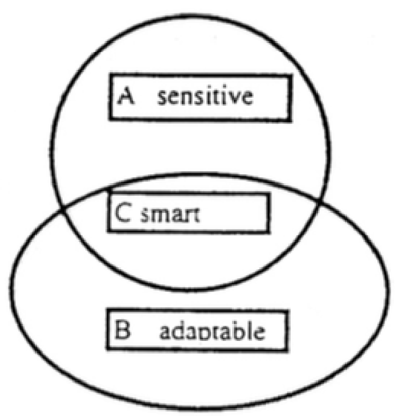

Figure 1. Schematic classification of smart materials.

Passive Smart Materials

have the ability to respond to environmental conditions in a useful manner, often incorporating self-repair mechanisms or stand-by phenomena which enable the material to withstand sudden changes in its surroundings.

ex) Ceramic Varistors - ZnO_2

When struck by high voltage lightening, a ZnO_2 varistor loses most of its electrical resistance and the current is by-passed to the ground. The resistance change is reversible and acts as a stand-by protection sensor.

PCT Thermistors

show very large increase in electrical resistance at the ferroelectric phase transformation near 130^{o}C. The jump in resistance enables the thermistor to arrest current surges, acting as a protection element.

Active Smart Materials

sense a change in the environment, and using a feedback system, makes a useful response. It is both sensors and actuators.

ex) Electrically Controlled Automobile Suspension System - Toyota, Lexus

A piezoelectric sensor detects road irregularities and feeds the signal into a piezoelectric actuator system, which automatically resets the suspension to compensate for the irregularity. The whole process takes only a few milliseconds, thus continuously damping bumps and dips to give smooth ride.

Table A. Currently Studied Engineering Concepts of SMA Composites

Passive

Impact damage resistance improvement[3]—The extremely high strain energy absorption capacity of SMA wires can substantially improve the impact damage resistance of otherwise brittle thermoset composites.

Vibration damping[4]—The high damping capacity of SMA elements can be used to increase the damping capacity of composite beams.

Strength improvement—Longitudinal strength of the composite can be significantly improved by embedding SMA wires capable of absorbing mechanical energy.

Creep resistance improvement—Damage of epoxy matrix composites involves matrix cracking, delamination, and fiber breakage. Embedding SMA wires may significantly slow down these processes.

Active

Shape control[6]—Prestrained SMA wires embedded off the neutral axis of the composite plate, rod, beam, etc. may, when activated, change the shape of the composite.

Natural vibration frequency control[5]—Natural frequencies and amplitude of mechanical vibrations of composite plates can be actively modified by activation of the embedded SMA wires.

Acoustic radiation and transmission control[13]—Activated SMA wires shift the natural vibration frequencies of the composite away from the frequencies suitable for sound transmission and radiation.

Active damage control[14]—Activation of embedded SMA elements can be used to close matrix cracks or to locally reduce matrix stresses close to critical stress levels.

Deflection control[15]—SMA elements, when activated, can return the deformed structure to its original shape.

Stiffness and modulus control[16]—Modification of the elastic properties of the composite plates or beams (e.g., bending stiffness, can be achieved by the activation of embedded SMA wires).

10-2. Types and Fabrication Processes of Smart Composite Materials

1. Shape Memory Alloy Reinforced Smart Composite

Shape memory alloys were integrated within monolithic or composite host materials to produce the desired components whose functionality or static and dynamic properties could be enhanced or actively tuned in response to environmental changes.

1) Shape Memory Alloys	+	Polymer Matrix
(Fibers, Wires, Ribbons, Particles, Thin Films)		(Polymer Matrix Composite)
Ni-Ti		Graphite/Epoxy
Ni-Ti-Pd-W		Glass/Epoxy

Passively, the shape memory alloy fibers are used to strengthen the polymer matrix composites, to absorb strain energy, and to alleviate the residual stress and thereby improve the creep or fracture resistance by stress-induced martensitic transformation.

Actively, the embedded SMA fibers are activated by electric current heating and hence undergo the reverse martensitic transformation, giving rise to a change of stiffness, vibration frequency and amplitude, acoustic transmission or shape of the composite. As a result, structural tuning, modal modification or vibration and acoustic control can be accomplished through :

i) the change in stiffness of the embedded SMA, or

ii) activating the prestrained SMA to generate a stress which will tailor the structural performance and modify the modal response of the whole composite system just like tuning a guitar string.

Embedded or bonded SMA fibers are elongated and constrained from contracting to their normal length.

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Curing to become an integral part of the smart composite

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Activating by passing a current through the SMA fibers, they will try to contract to their normal length and therefore generate a large, uniformly distributed shear stress along the length of fibers.

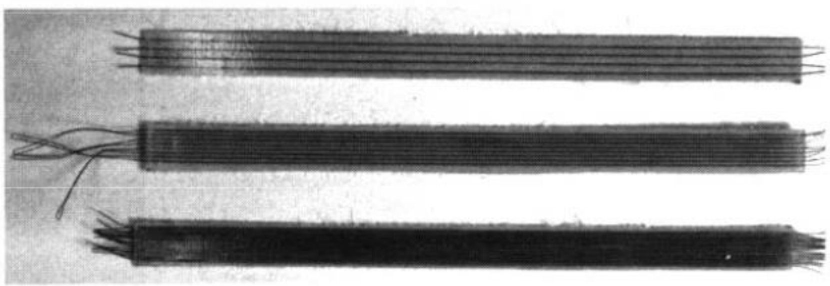

Figure 1. Three SMA composite samples with different volume fractions of thin Ni-Ti-Cu SMA wires embedded in a Kevlar® reinforced epoxy matrix produced at EPFL, Lausanne, Switzerland.

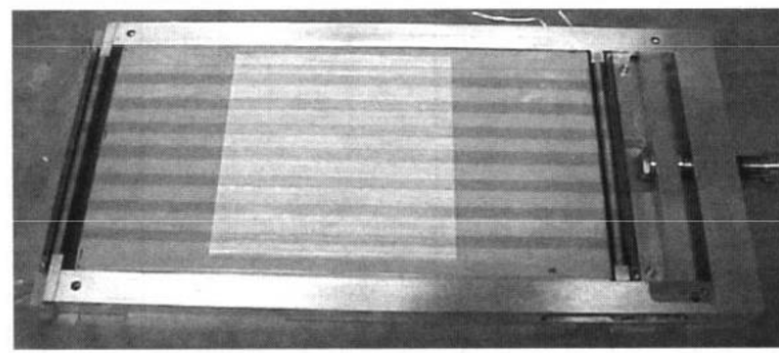

Figure 2. An example of a frame used in the fabrication of SMA composites to keep the SMA wires prestrained during the curing treatment. The frame has been made at EPFL, Lausanne, Switzerland.[9]

2) Shape Memory Alloys	+	Metal Matrix
(Fibers, Wires, Ribbons, Particles, Thin Films)		
Ti-Ni		Al Matrix
Ti-Ni-Pd-W		Ti
Cu-Zn-Al		

Fabrication Process

i) SMA fiber reinforced Al composites are prepared and fabricated by using conventional fabrication techniques.

ii) The as-fabricated composites are heated to high temperature to memorize the shape of fibers.

iii) The composites are cooled to lower temperature, preferably in the martensite state.

iv) The composite are subjected to proper deformation at the lower temperature to enable the martensite twinning or stress-induced martensitic transformation.

v) The prestrained composites are heated to high temperatures, preferably above the austenite finish temperature, A_f, wherein martensite detwinning or the reverse transformation from martensite to austenite takes place. The SMA fibers will try to recover their original shape and hence tend to shrink, introducing compressive internal residual stresses in the composites.

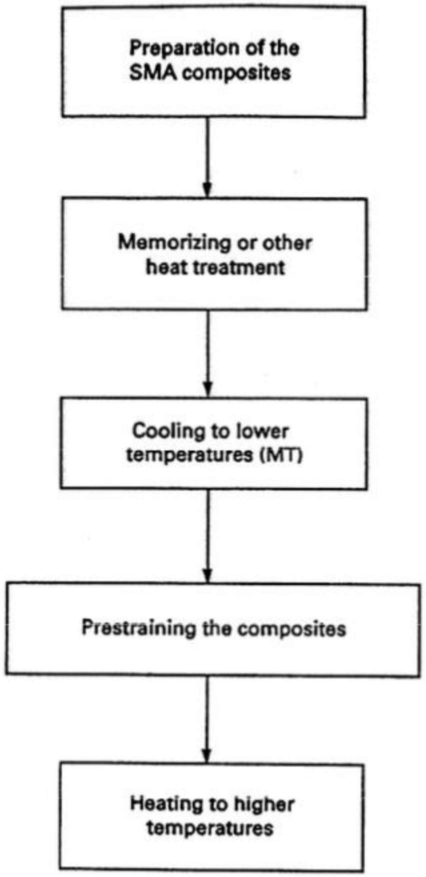

Figure 1 Design concept of SMA-reinforced composites

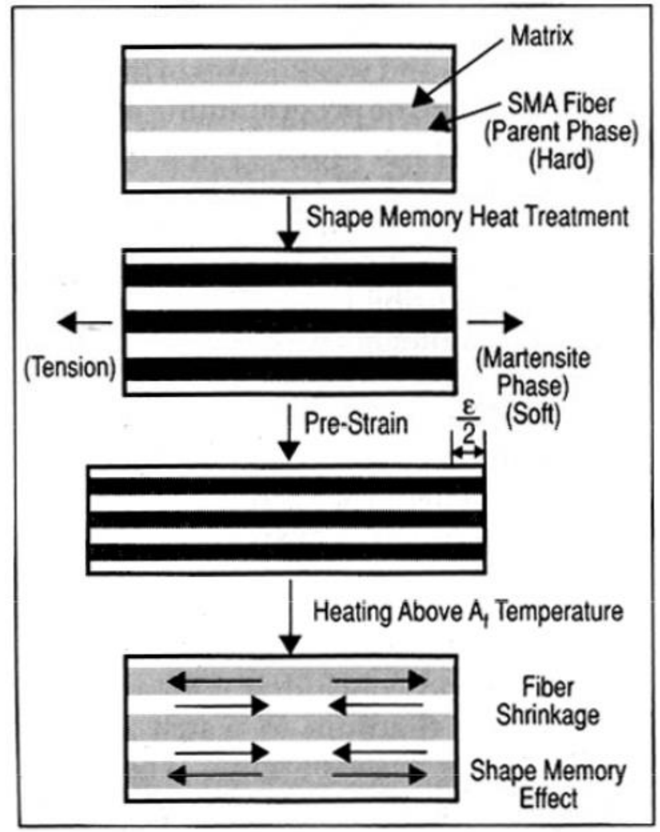

Figure 1. Design concept of a smart composite with SMA.

Fabrication Processes for SMA Fiber Reinforced Metal Matrix Composite

Hot Pressing Process

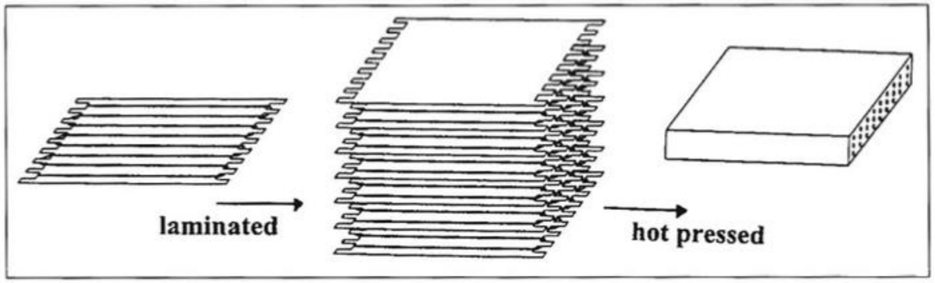

Figure 3. Configuration of smart-metal matrix composite with continuous SMA fiber reinforcement.

Hot Extrusion Process

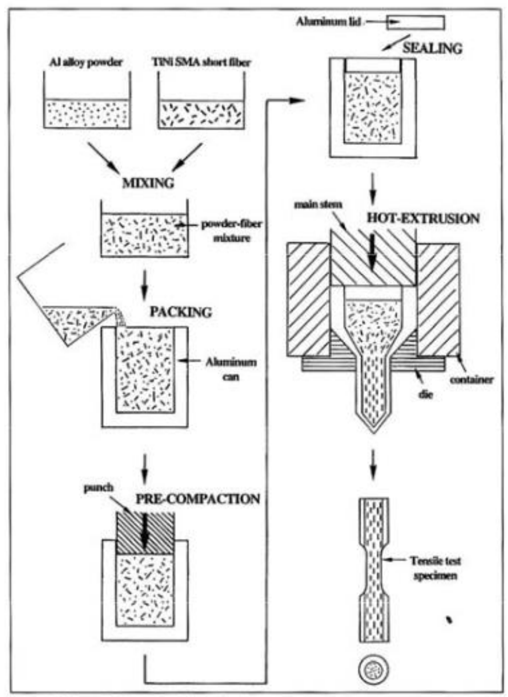

Figure 5. Schematic illustration of hot extrusion process.

Powder Metallurgy Process

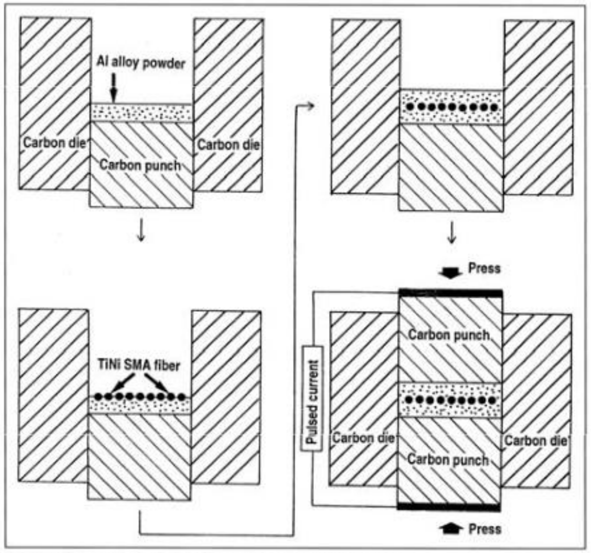

Figure 6. Schematic illustration of spark plasma sintering process.

Sheath Rolling Process

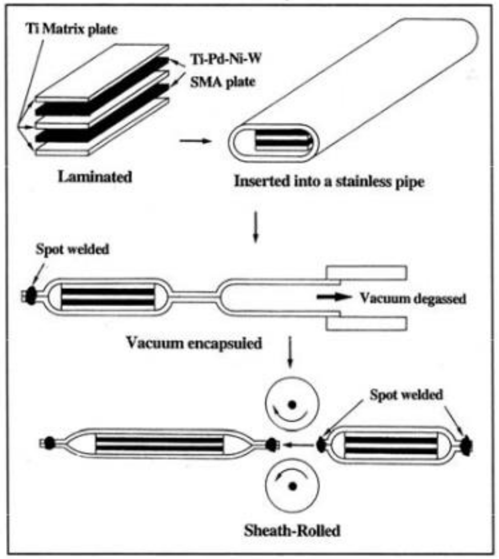

Figure 7. Schematic illustration of sheath rolling process.

2. Piezoelectric Ceramic Reinforced Smart Composites

Piezoelectric Materials	+	Polymer Matrix Composites
- Single Crystalline SiO_2 (Quartz)		- Glass/Polyester
- Polyvinylidyne Fluoride (PVDF)		
- $Pb(Zr,Ti)O_3$		

When excited by an electric current, a piezoelectric material is strained and its electrical impedance is directly related to the deformation. Depending on the shape and nature of the piezoelectric material, the orientation of polying axis and the location of the electrode, the piezoelectric material will present different resonance modes which are characterized by their natural frequencies and amplitudes. Moreover, when such an piezoelectric material is inserted in a matrix, its electrical impedance will depend on the viscoelastic characteristics of surrounding matrix.

ex) Soft Ceramics having Controlled Compliances

PZT sensor/actuator combination is used to produce"soft ceramics", in which the sensor feels a stress and an actuator retracts the ceramics, giving the ceramic a rubber-like feel.

The smart sensor/actuator system can mimic a very stiff solid or a very compliant rubber. This system retains great strength under static loading, making the smart composite especially attractive for vibration control.

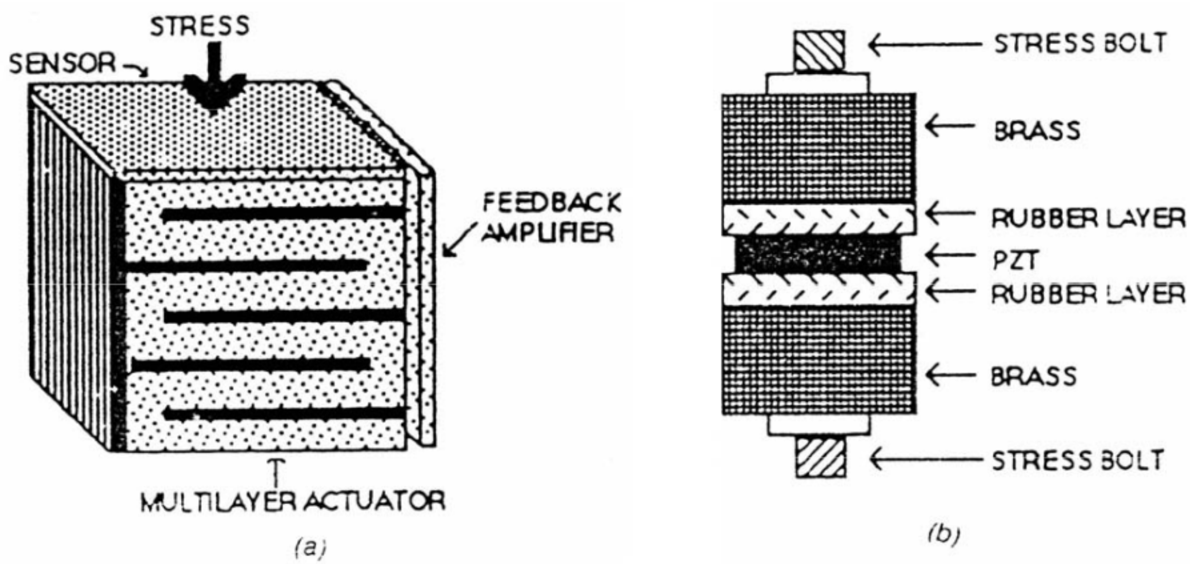

Figure 3. Examples of piezoelectric-based smart materials. (a) The "soft" ceramic, (b) the tunable transducer.

Tunable Transducer

Smart material can senses a change in the environment and responds by altering one or more of its property coefficients. Such smart material can tune its sensor and actuator functions in time and space to optimize future behavior. With the help of a feed back system, a smart material becomes smarter with age or time.

Let’s consider a composite transducer consisting of a piezoelectric ceramic (PZT) transducer, thin rubber layers, metal head and tail masses, all held together by a stress bolt. The change in resonance and Q can be modeled with an equivalent circuit in which the compliance of thin rubber layers are represented as capacitors coupling together the large masses of the PZT transducer, metal head and tail masses.

Application of transducers include fish finders, gas igniters, ink jets, micropositions, biomedical scanners, piezoelectric transformers, filters, accelerators and motors.

10-3. Applications of Smart Materials

- Smart medical systems for the treatment of diabetes with blood sugar sensors and insulin delivery pumps
- Smart airplane wings that achieve greater fuel efficiency by altering their shape in response to air pressure and flying speed
- Smart toilets that analyze urine as an early warning system for health problems
- Smart structures in outer space incorporating vibration cancellation systems that compensate for the absence of gravity and prevent metal fatigue
- Smart houses with electrochromic windows that control the flow of heat and light in response to weather changes and human activity
- Smart tennis rackets with rapid internal adjustments for overhead smashes and delicate drop shots
- Smart muscle implants made from rubbery gel that respond to electric fields
- Smart dental braces made from shape memory alloys
- Smart hulls and propulsion systems for navy ships and submarines that detect flow noise, remove turbulence, and prevent detection
- Smart water purification systems that sense and remove noxious pollutants