# Shape Memory Polymers and Composites in Aerospace Applications

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***Abstract*:- Shape memory polymers (SMP) and SMP based composites are typical smart materials, which can transform from their temporarily fixed configuration to their original configuration under external stimuli. Shape memory effect is an intrinsic property of polymers and changes according to different molecular weight and components of different polymers. They have inherent advantages like lightweight, large recoverable deformation capability, biocompatibility, etc. This paper reviews status of SMP nanocomposites, SMP filler composites in aerospace applications. We will discuss about the materials and structures which could be used and also about the general mechanism of SMP's and their composites, which have great potential for novel aerospace applications development.**

***Keywords: Shape memory polymers, SMP, polymers, composites, aerospace, applications***

## INTRODUCTION

SMP's are type of macro molecules which respond to external stimulus by changing its macroscopic properties (such as shape and color) and then recover its original shape from its temporary shape. SMPs have advantages of being lightweight and inexpensive and of having low density, high shape deformability, good biodegradability and an easily tailorable glass transition temperature compared with shape memory alloys (SMAs) and shape memory ceramics. Main drawbacks of SMPs are low recovery stress, low deformation stiffness, smaller energy output and longer recovery time.

To overcome these deficiencies, shape memory polymer composites (SMPCs) have come into existence. The results of studies on SMPCs indicate that they have superior strength, higher stiffness and certain special characteristics determined by what fillers are added, which can offer further advantages over SMPs.

SMP based composites are generally divided into particles-reinforced and fiber-reinforced composites. Particles-reinforced SMPCs, whose fillers are carbon black, carbon nanotubes, $Fe_3O_4$ nanoparticles, etc are used more as functional materials. Fiber-reinforced SMPCs, whose fillers include carbon, glass and Kevlar fibers, etc are usually used as structural materials because of their good mechanical properties.

There are some excellent reviews about the development and application of SMPs and SMPCs, such as a review written by Liu et al on SMP's and SMPC's and their applications in Aerospace applications. In addition to this, an article by Fengfeng Li et al, explains us about the progress of shape memory polymers and their composites in aerospace applications. This review focuses on the SMP/SMPC materials and their applications in aerospace field, which includes reflecting antennas, SMPC hinges, etc. Our goal is to track the applications, who have already completed the space experiments, and to list new applications, who are potential for the aerospace-based industry.

## MECHANISM OF SMP AND SMPC'S

SMPs and SMPCs most valuable characteristics are their variable material properties above and below the transition temperature (glass transition temperature (Tg) or melting transition temperature (Tm)). Polymers are covalent or physically cross-linked, exhibiting viscoelastic to large strain above either Tm (crystalline polymers) or Tg (amorphous polymers), and elastic to small strain at low temperature. At the temperature above Tm/Tg, the polymer chain segments deform freely, and twist randomly around the skeleton bond, thereby leading to maximum entropy. The shape memory mechanism for polymers with significant shape memory property involves, accomplishment of shape programming by locking the polymeric segments without creep; a sharp transition of the modulus corresponding to temperature, which would promptly lead to a temporarily fixed shape at low temperature and stimulate shape recovery at high temperature; viscoelasticity above Tm/Tg which ensures a relatively complete shape recovery without residual strain.

The low mechanical properties of SMPs are limiting factors for their commercial applicability. Therefore, to overcome these drawbacks, SMPC's are developed. Reinforcing capability of continuous fibers is highest, followed by short fibers and finally particles. SMPCs for aerospace application is primarily continuous fiber reinforced SMPCs, normally carbon fiber. These continuous fiber reinforced SMPCs are able to undergo large macro bending deformations. Micro buckling will take place under large bending ratio when SMPC is heated to a temperature above Tg/Tm. Here, SMPC does not have enough stiffness to support those fibers in compression and thereby leading to microbuckling. It should be noted that the thickness of the SMPC is usually less than 2 mm, since a thicker laminate or a laminate with large modulus would have a large shear force to prevent the bending of fibers or damage the matrix.

## EFFECT OF VARIOUS SPACE ENVIRONMENTS AND FACTORS ON SMP/SMPC

The selection of new raw materials for aerospace applications needs to withstand various ground simulated space conditions such as UV radiations, atomic oxygen, plasma environment(ions and electrons), space debris, etc which can lead to degradation of material in space environment , lead to damage in the structure and reduce the system's reliability. In this section, we will have a look through some of the important factors, which will affect the structure's service life in the space environment

***1. Vacuum***

If vacuum environment is too high, it can lead to material degassing, sublimation and even loss in mass and reduction in physical and dielectric properties. When levels of vacuum become too high, gas which is adsorbed onto the material surface or dissolved into the material, may become detached and will be released. If this gas undergoes condensation and settles onto the device, the device might get contaminated.

Apart from this, the high vacuum may lead to induction of space charges, which might cause breakdown of instruments or short circuit and cold welding of materials, which might cause obstruction of moving parts.

***2. Thermal cycling***

Every spacecraft experiences large temperature differences in the orbit. Two reasons for this kind of temperature difference are- Firstly, due to difference between illuminated surface and the non-illuminated surface, and the other one is the alternate temperature change due to the alternate moving in and out of earth's shadow. Long-term thermal cycling can lead to uneven thermal stress and microcracking of materials, thereby deteriorating physical and mechanical properties.

***3. UV radiation***

With a wavelength of 10-400nm, UV radiations have very high photon energy, which causes cleavage of chemical bonds, thereby leading to microcracks and embrittlement, followed by aging. It also deteriorates the mechanical and optical properties of thermal surface coatings, composite adhesives, etc. Shape memory behavior experiments along with FTIR indicate that UV radiation does not change the chemical bond of the above SMPs, and their shape memory properties remain stable.

## STIMULUS METHODS OF SMP'S AND SMPC'S

As a result of various external stimuli and polymer matrices, SMP and SMPC's exhibit shape- memory effect. Heat and Electricity-induced SMPs and SMPCs are most typical stimulus methods. Additionally, water, magnetic field, light and solvent can also actuate the shape memory recovery of SMP and SMPC structures.

***1. Thermally responsive SMP's & SMPC's***

Most widely researched and common type. Thermo-mechanical properties and applications of thermal responsive SMP structures are widely studied.

The deployment of thermal responsive SMPs and SMPCs only occurs in a one-dimensional (1D) direction, and it is a straightforward process. Currently, SMPs and SMPCs are being used for packaging and deployment of much complex structures, such as solar arrays or morphing wing structure models, when the raw materials are selected effectively.

***2. Electro-responsive SMP's and SMPC's***

Another common type of structure, in which electrically conductive fillers are added into the SMP matrices to form electrically sensitive structures. Various conductive nanofillers like SWCNT, MWCNT's were reinforced into SMP matrices to improve electrical conductivity. SMPC structures demonstrated a good shape recovery effect with varying reinforcing phase volume fraction. Additionally, carbon nanopaper is a new reinforcing material, which is being used nowadays. The changing in trends of electrical resistivity and conductivity of a SMP reinforced with nanocarbon powders or fibers are analyzed by Leng et al. Owing to the relation between strain and electrical resistivity, along with different temperatures, electro-responsive SMPs can be manufactured to be smart strain structures or temperature sensors in applications.

***3. Other responsive SMP's and SMPC's***

Apart from the above-mentioned stimulus methods, water/solvent, light radiation and change in magnetic field will also play a role in future applications. Light-responsive SMPs and SMPCs can be classified into two types: the intrinsically light-induced SMP, they are sensitive to only certain wavelength of light and are independent of the temperature effect, and the indirect thermal actuation SMPC, which absorb infrared light and heat effectively and actuate the structure to recover its original shape.

Magnetic-responsive SMPCs mainly consist of SMP matrices and magnetic fillers, such as Fe2O3, Fe3O4 and Ni particles; the shape memory effect can be stimulated using an alternating external magnetic field. Water/solvents can also be used. They tend to behave as plasticizers and thereby reduce the glass transition temperature and trigger the shape recovery process at relatively low temperature compared to the original SMP/SMPCs.

## APPLICATIONS OF SMPC'S IN AEROSPACE

There are some disadvantages, traditional structures are intrinsic and they are high weight, high cost and high deployable shock effect. This takes up much room in spacecraft and decreases the effectiveness of aerospace missions. To overcome these limitations, some new materials and structures have been developed, which will improve the effective space usage in the device.

***SMPC Hinge***

In the deployment process of space-deployable structures a hinge is used as the driving factor. The main factors to assess its effectiveness is recovery precision and shock effect. Traditionally, deployment depends on a mechanical hinge. However, integrity of mechanical hinge and large shock effect of spring steel hinge increases the hinderance in the development of aerospace applications. To overcome this issue, a new type of hinge composed of elastic memory composite (EMC) materials was introduced, which reduced the moving parts and shock effect.

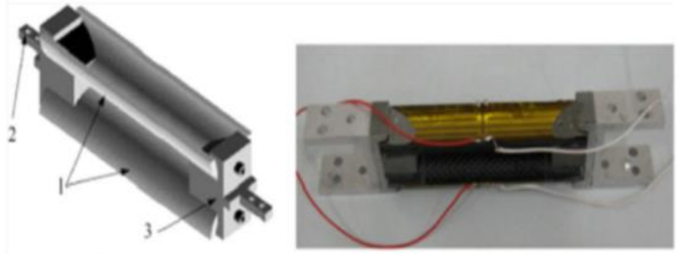


Figure 1: SMPC Hinge

***SMPC booms***

Booms are used to support the tip payloads in satellites. Traditionally, the design of a space deployable boom involves complex assembly and high weight and control mechanism because the materials selected are mostly metals. Researchers have explored many methods to overcome this problem. Deployable booms can be divided into two classes: 1. classical traditional booms and 2. novel SMPC booms. The classical traditional space-deployable booms include extendible

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booms, tubular and collapsible truss booms actuated by motor. In contrast, the novel SMPC not only has simple structure, but also it has packages and deploys without mechanical devices. Hence, increasing interest for space-deployable structures of the unique characteristics of SMPCs have aroused. The novel types of SMPC booms can be divided into storable tubular extendible member (STEM) booms, coilable truss booms and foldable truss booms. The main component of the SMPC boom is longeron, which provides the deployable driving force and undergoes the tip payloads at the end of deployment. The bending mechanical properties and deployment dynamics must be considered in aerospace application due to SMPC hinges/booms needing to undergo flexural deformation and have minimal strain. The microbuckling response of reinforced EMC laminates, reported by CTD Co. The fiber microbuckling can undergo higher flexural deformation without damage at high temperature and store the deformation state at low temperature, this is shown by results. The microbuckling gradually disappears and the original shape is gradually recovered when the EMC material is reheated.

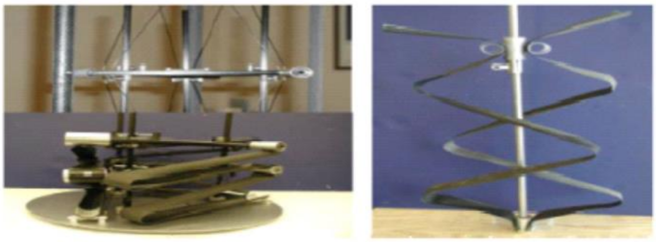

Figure 2: SMPC Booms

***SMPC reflector antennas***

Communication tool between the satellite and Earth in space which can provide necessary information about space matter is known as antenna. Antenna is very important in the communication tool. To measure deployable antenna working properties, the reflector aperture and precision are two important parameters.

An inflatable antenna is designed using flexible materials which is an important type of deployable reflector. Before launch the antenna is packaged into a small volume. The antenna is released, inflated and hardens because of the physical or chemical effect when the spacecraft is in space. In 1996, NASA successfully completed the in-orbit experiment. Sufficient surface reflector precision was obtained. Now days, in order to eliminate the air pressure leakage issue, SMPCs are used for fabrication of the main parts of the inflatable antenna.

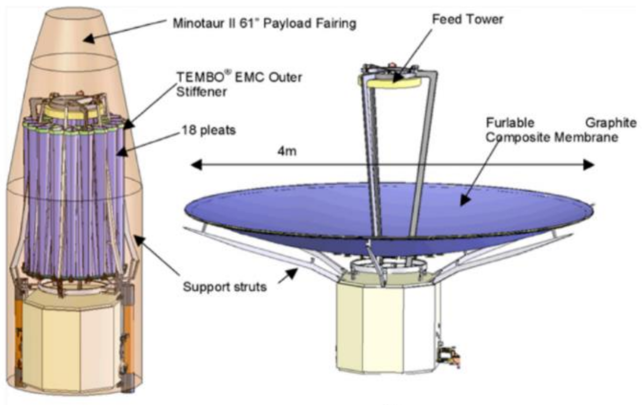


Figure 3: SMPC reflector antennas

***Solar arrays and deployable panels***

Solar Arrays are energy generation subsystems in space-deployable structures. Before launch, solar arrays are used to obtain energy in space and are commonly packaged in the vehicle. Once they are enter in orbit, they released to deploy and collect energy and their efficiency depends upon a large deployment area.

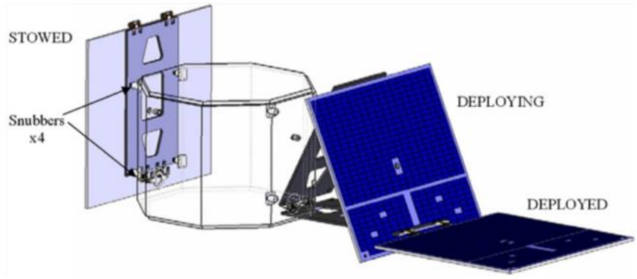


Figure 4: Solar array design

***Morphing structures***

The idea of morphing an aircraft's shape is far from new. For designing, the inspiration originates from birds flying free in the air and changing their flight posture according to the air flow. However, traditional aircraft can only carry out a single mission in a flight such as a Boeing 747 used for long-distance transport mission or an F-17 being used for attack mission. Morphing vehicles were introduced to improve flight performance, to overcome this problem and efficiently alleviate structural deterioration. Today, researchers are greatly interested in designing new types of morphing wing skin which involves SMPs and SMPCs, they can change their shape according to the temperature or other external stimulus and maintain normal efficiency.

***SMP and SMPC mandrels***

Traditionally, there are two methods to overcome the fabrication problem of complex-curved structures: 1. multi-piece metal mandrels and 2. water-soluble mandrels. Although multi-piece metal mandrels can successfully satisfy the design precision, for this a significant amount of time, labor, energy, and cost is required to design, fabricate, assemble and demold these structures. On the other hand, the fabrication of water-soluble mandrels is relatively complex. The main steps involve the preparation water-soluble materials (sand or salt) and a rigid support rod which forms pre-deformation shape of the structures; injecting water into the mandrel to dissolve the sand or salt; filament winding and curing and finally, the structure can be formed after cleaning the internal impurity. CTD have fabricated linerless composite tanks and analyzed the mechanical properties using this method. The disposable usage and residual noxious materials severely hinder the development and modification of water-soluble mandrels. However, SMP or SMPC mandrels are reinforced with a high strain fiber and they have advantages of variable stiffness based on a lower product cost, external temperature, reusable usage and an easy demolding process, which is becoming a new developing direction of complex-curved structural manufacturing techniques. A bottle-shaped mandrel and airduct-shaped mandrel is fabricated by CRG and verified the technique feasibility of SMP. To satisfy the various work environments in the company, different types of SMP materials reinforced with fibers were produced. The

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mechanical properties of thermoset styrene SMP bottle-shaped mandrels and air-dust-shaped mandrels are investigated by Leng et al. The results demonstrate the reusable and good deformation usage properties of the SMP mandrels: the structures have good shape recovery ratio and good shape fixity after several cycles, and the demolding and deformation process are easily controlled with temperature.

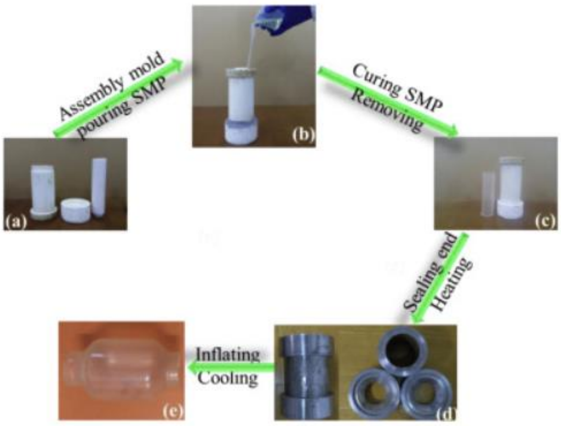


Figure 5: Fabrication process of bottle-shaped SMP mandrel

## CONCLUSIONS

SMP's and SMPC's are one of the most advanced materials, which are playing a major role in the aerospace field but to achieve commercial applications, we need to integrate a lot of excellent functions, such as good space radiation resistance, stable shape memory performance, suitable mechanical properties, simple and effective stimulus methods, etc. Owing to the remarkable research which has taken place in the last few years, various components have been developed to meet the need of space deployable structures such as reflector antennas, morphing structures, solar arrays and deployable panels.

One of the most striking characteristic of SMPs and SMPCs is their variable stiffness under varying different external stimuli. SMPC hinges/booms can be deployed to realize the shape recovery of components and structures, which can provide deploying force and damping during the process and at the end of deployment lock the shape to support the deployed structures.

Apart from the advantages, there are some challenges to the applications of SMPC in aerospace. Mainly it is the high-temperature. SMPC should be suitable for working under the harsh space environment.

Considering all of its unique advantages, such as low density, light in weight, high strength–weight ratio, low part count, simple design, good manufacturability, high shape deformability and an easily tailorable glass transition temperature. Shape memory polymers and shape memory polymer composites are expected to develop in multiple dimensions and have great potential applications in aerospace in the near future.

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